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Volume 105
Number 3
Fall 2019

Journal of the
WASHINGTON
ACADEMY OF SCIENCES

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Journal of the Washington Academy of Sciences (ISSN 0043-0439)

Published by the Washington Academy of Sciences

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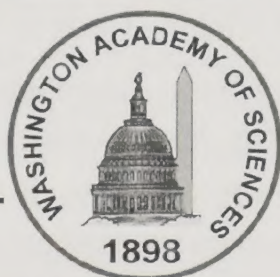
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EDITOR'S COMMENTS

Presenting the 2019 Fall issue of the *Journal of the Washington Academy of Sciences*.

This issue of the *Journal* presents three papers. We have a slightly new format. The general information pages have moved to the front of the issue followed by the research papers. At the end is our first SciBite contribution. First up is an astronomy paper on NGC 4622, a galaxy. The characters NGC stand for New General Catalog, an astronomical catalog that contains a numbering method for celestial objects. The galaxy discussed in the paper is number 4622 in the Catalog.

Next is another astronomy paper on the possibility of living in lava tubes on Mars.

The last paper has two parts: a background article that precedes the main article on lead in the drinking water in Washington DC.

The latest science news mentions an impossible black hole discovered in the Milky Way. We end with an AstroBite on this topic.

The *Journal* is the official organ of the Academy. Please consider sending in technical papers, review studies, announcements, SciBites, and book reviews. Please send manuscripts to wasjournal@washacadsci.org. If you are interested in being a reviewer for the *Journal*, please send your name, email address, and specialty to the same address. Each manuscript is peer reviewed, and there are no page charges. As you can tell from this issue we cover a wide range of the sciences.

I encourage people to write letters to the editor. Please send email (wasjournal@washacadsci.org) comments on papers, suggestions for articles, and ideas for what you would like to see in the *Journal*. I also encourage student papers and will help the student learn about writing a scientific paper.

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Sethanne Howard



Journal of the Washington Academy of Sciences

Editor Sethanne Howard

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NGC 4622: Unusual Spiral Density Waves and Calculated Disk Surface Density

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Abstract

NGC4622 was initially known to have a beautiful spiral pattern composed of two trailing spiral arms. The arms are outlined by stellar associations, a prototypical two-armed density wave pattern. Later Byrd et al (2008 and references) discovered that the outer pair leads (the opposite of what was previously thought) along with a new single trailing inner arm. It is shown here that NGC4622 has an unusual pattern with a textbook density wave arrangement of stellar associations relative to stellar arms. Also, NGC4622's unusual flat then rising rotation curve, its co-rotation radii, and arm inclinations can be used to calculate the surface mass density of the disk in both arm regions. The surface density is comparable to that in our Milky Way out to ~ 5 kpc then it rises to much larger values at 8 kpc radius. So, NGC 4622 is an even more exceptional galaxy with a flattened dense outer disk deduced from its beautiful outer leading arm pair and rising rotation curve.

Introduction

IN HIS EXCELLENT TEXT, *The Physical Universe*, Frank Shu (1982) included a photo of NGC4622 describing it as “a beautiful spiral pattern composed of two trailing spiral arms.” The arms are outlined by “brilliant associations” like “beads on a string” *i.e.*, it is a prototypical example of a two-armed density wave pattern. Previous work (Byrd *et al* 2008 and references) discovered that the outer pair leads (the opposite of what was previously thought) along with a new single trailing inner arm (not mentioned by Shu). As discussed here, NGC4622 is a clear example of an unusual density wave patterns with two kinds of arms. We use NGC4622's unusual rising rotation curve, its co-rotation radii, and its arm inclinations to calculate the surface density of the disk in the two arm regions.

Arm sense from positions of associations relative to stellar arms

In Figure 1 an outer pair of arms (1 and 2) winds outward clockwise (CW). There is an inner single arm (3 in right hand frame) which winds outward counterclockwise (CCW). According to conventional density wave descriptions, the outer pair should trail outward CW, *opposite* a CCW sense of disk orbital motion.

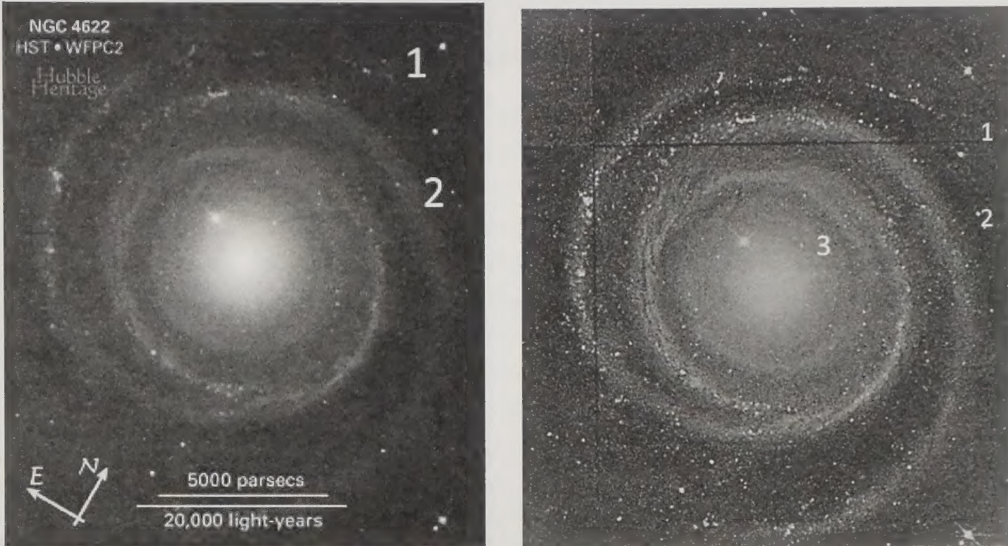


Figure 1. HST images of NGC4622: Left, color. Image with compass points on sky. And scale 5000 pc =29.7 arc sec ("). Right, a sharper view of associations (blue white) and stellar arms (tan).

Examining the right image of Figure 1, dark gas/dust cloud silhouettes are much clearer on the SE side. That edge is thus thought to be turned toward us and the NW away at an angle of $\sim 19^\circ$. Radial velocity observations indicate that the NE upper end of node line recedes and the SW end approaches, so orbits are clockwise (CW) on the sky. As discussed in our earlier papers, the outer pair of arms leads outward CW and the single inner arm trails, contrary to the usual theoretical expectations.

Leading and trailing arms and their co-rotation radii

Arm inclinations and co-rotation radii CR (which occur where the orbital Ω^i equals the arm pattern speed, Ω_p) can be determined from the IVB Fourier components. The boundary between leading and trailing arms is observed to be near radius, $r = 25$ to 30 arc sec ("). In Figure 2 NGC4622's rotation curve (v in km/sec) is fairly flat with increasing radius out to $\sim 30''$.

In this region, the orbital angular rate ($\Omega = V/r$) declines with r . At larger r , an unusual rising rotation curve appears so that Ω rises with increasing radius. (Byrd et al 2008 and references therein). A trailing arm would be created inside $\sim 30''$ where the Ω declines with radius and a leading arm pair outside $\sim 30''$ where the Ω rises.

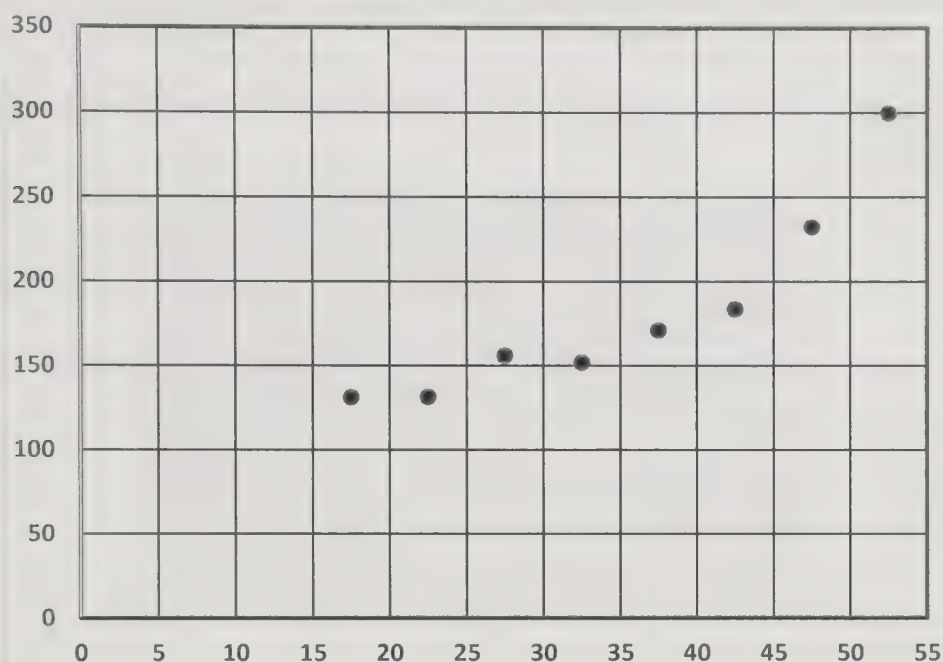


Figure 2—Measured NGC 4622 orbital rotation curve (speed, V , in km/sec) versus radius (r in $''$) (See Byrd *et al* 2008 and references therein).

Stellar association locations relative to the older stellar arms provide additional support for the unexpected arm winding. In Figure 1, (right frame) the “beads on a string” NE arm 1 winds outward CW in the HST image. Gas clouds enter the more slowly turning stellar arm 1 on the *convex* side outside the outer co-rotation radius, CR2, at $36.4''$ (5.94 kpc) marked as the solid circle in Figure 3. These clouds later become short-lived associations as seen on the *concave* side of arm 1 in the image. At immediately smaller radii than $36.4''$, the associations of arm 1 are on the *convex* side as the arm catches up to the slower gas clouds which light up on the other side. The solid CR2 circle and orbital motion arrows outside and inside relative to CR2 are shown in Figure 3. The stellar arm motion arrows are light colored and the gas cloud motion arrows are dark colored.

In Figure 3, the inner single arm 3 trails outward CCW from the center through an inner co-rotation radius (CR1) at $21.3''$ (3.53 kpc) marked with a dashed circle. The orbital motion arrows are shown inside and outside the inner CR1 are included in Figure 3. Unfortunately, in arm 3 of Figure 1 the individual associations are not so clear relative to the stellar arm as those in outer pair of arms. However, position angles of the different IVB color Fourier arm components also show the cloud/association formation sequence and permit accurate determination of both the outer CR2 and the inner CR1 radii.

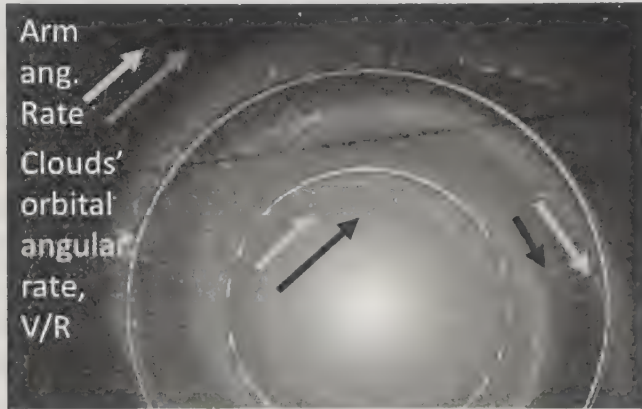


Figure 3. Relative gas cloud and stellar arm positions and motions in NGC 4622 inside and outside CR1 (dashed circle) and CR2 (solid circle).

Figure 4 shows the peak position angles for the single inner arm one-fold $m = 1$ color component (Byrd *et al* 2008). The sequence BVI indicates the position angles of the color components. Going outward, the arm position angle increases upward, CCW. This arm thus trails. Note that the Fourier component of the $m = 1$ IVB sequence does a 180° angle jump at the inner CR1 radius ($21.4''$). This matches the theoretically expected behavior for interior to exterior crossing the inner CR1 for the single arm. Note the CW IVB downward sequence interior to CR1 as the orbiting disk material passes the slower inner CR1. The reverse (BVI) sequence downward is seen where the CW disk orbital motion is slower exterior to the CR1 angular rate.

As shown in Byrd *et al* (2008), there is a similar (but inverted) Fourier component $m = 2$ IVB order switch at the outer CR2 ($r=36.4''$) like the individual associations relative to the stellar arm we discussed in Figure 1. The Ω must increase outward with radius at the outer CR2, confirming

the leading outer pair of arms. There is no 180° jump in this case since there are two symmetrically placed arms.

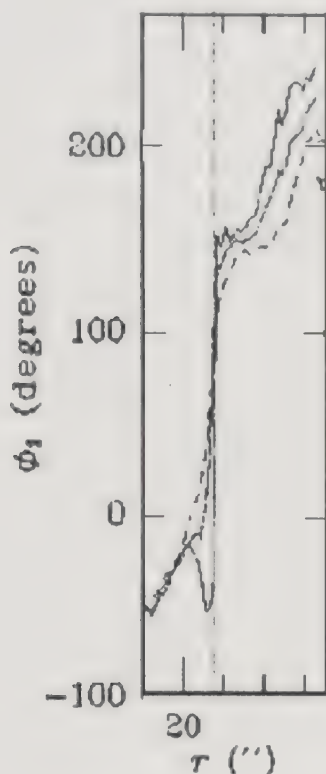


Figure 4. Position angle, ϕ , of inner single arm shown as Fourier components versus r . The inner single arm $m = 1$ component is shown. Orbital motion is downward (CW), opposite to the CCW position angle that increases upward.

A smoothed orbital velocity versus radius fit through the Figure 2 data is shown in Figure 5a. The fit requires that the observed derivative of the angular rate versus radius is zero in neighborhood of $30''$ between the single trailing arm and the pair radius, outside this neighborhood it rises. Hence the trailing and leading senses.

Also used in the fitting are the co-rotation radii and their angular rates marked in Figure 5b with vertical dashed lines. The extended horizontal dashed lines from these two indicate the two pattern speeds, 5.87 km/s/'' for $\text{CR1} = 21.3''$ and 4.81 km/s/'' for $\text{CR2} = 36.4''$. With $5 \text{ kpc} = 29.7''$, these values correspond to 3.6 kpc and 6.13 kpc .

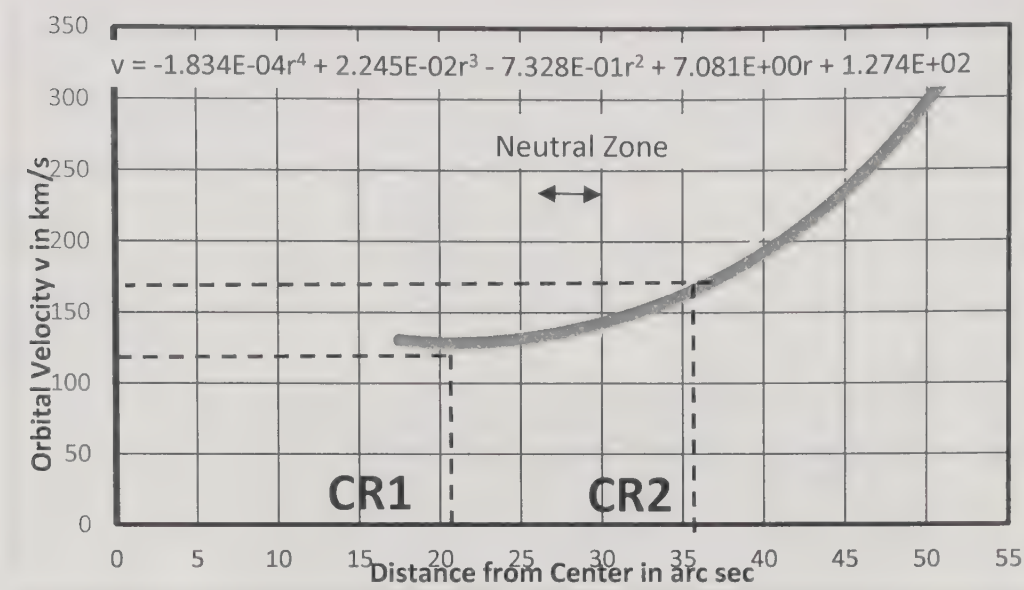


Figure 5a--Plot of v (km/s) versus r (") of a smoothed Excel 4th order polynomial. The fit requires that $d\Omega/dr = 0$ near $r = 30''$ and $v=138$ km/s and also includes the co-rotation radii, angular rates, CR1, ($\Omega = 125$ km/s/21.3") and CR2 ($\Omega = 175$ km/s/36.4"). Finally, extreme Ω s (130 km/s/17.5") and (330 km/s/52") are also used. Compare Figure 5a to Figure 2 to see the fit to the data.

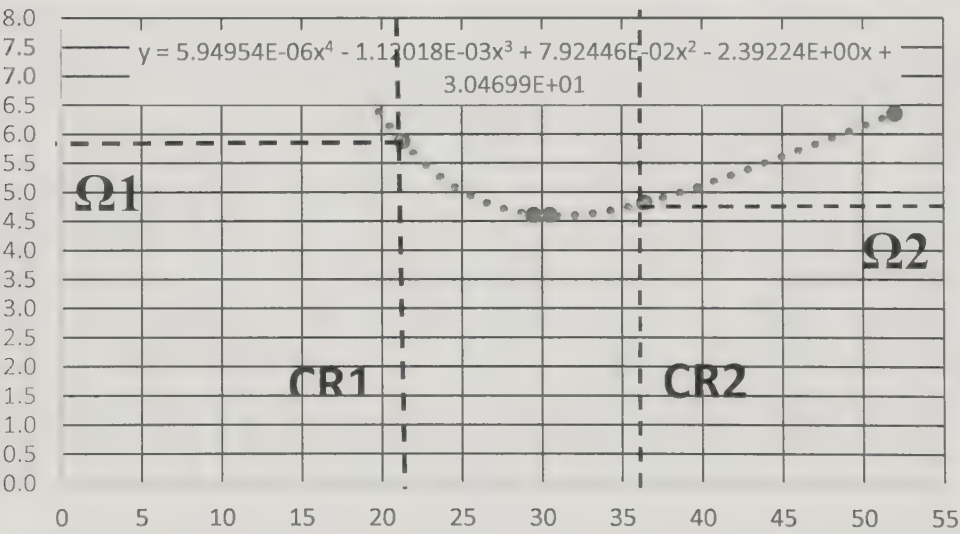


Figure 5b--Plot angular rate of (km/s) / r (") of a smoothed Excel 4th order polynomial. The fit requires that $d\Omega/dr = 0$ near $r = 30''$ and $v=138$ km/s and also includes the co-rotation radii, angular rates, CR1, ($\Omega = 125$ km/s/21.3") and CR2 ($\Omega = 175$ km/s/36.4"). Finally, extreme Ω s (130 km/s/17.5") and (330 km/s/52") are also used.

Inclination of Arms

Arm inclinations (i) are defined either for the single $m = 1$ arm or the $m = 2$ arm pair. These are the acute angles where the arms cross the two co-rotation circles shown in Figure 3 and at other radii circles also. For pedagogy we use the notation and refer to some of Shu's (1982) formulas. The arm radius of the one-fold arm increases with counter clockwise position angle, opposite the two-fold arm. The arm inclination definitions (prob. 12.11 and Eq. 4 Shu) are given by Equations (1) and (2):

$$|k| = \frac{m}{r \tan i}, \quad (1)$$

and

$$\tan i = \frac{\Delta r}{\Delta \phi r} = \frac{2\pi}{\lambda} \quad (2)$$

where λ is the wavelength. In typical spiral galaxies the inclination is nearly constant over the arms (Kennicutt 1981).

Disk Surface Density Calculation Application to NGC 4622

We now calculate the disk surface density of NGC4622. The dispersion relation provides a condition for stability determined by the competing self-gravity of surface density μ , velocity dispersion, and orbital angular rate, $\Omega = V/r$, and the shear. The dispersion relation is given by Equation (3):

$$(\omega - m\Omega)^2 = \kappa^2 + k^2 a^2 - 2\pi G |k| \mu \quad (3)$$

where m is arm multiplicity (See Prob. 12.11 and Eq. 1 in Shu 1982). It turns out that this relation is valid for winding arms as well as for circularly symmetric perturbations (Byrd 1995).

Here the epicycle frequency squared is given by Equation (4):

$$\kappa^2 = r^3 \frac{d}{dr} (r^4 \Omega^2) = 4\Omega^2 + 2r\Omega \frac{d\Omega}{dr} \quad (4)$$

(Prob. 12.8. Shu 1982). The wave frequency is given by Equation (5):

$$\omega = m\Omega_p \quad (5)$$

and the arm pattern speed is Ω_p .

Equation (3)'s left hand side can be described as the spring constant for oscillation of stars relative to the arm. If there is no surface density or velocity dispersion, pure epicycle oscillation is left. For harmonic oscillation the right side of equation (3) must be greater than zero. Assuming zero, the minimum disk velocity dispersion parameter for stability is Equation (6):

$$a_{\min} = \frac{\pi G \mu}{\kappa}, \quad (6)$$

(prior to Shu's Eq. 3), again also valid for winding arms (Byrd 1995, equation 12b).

The observed values of arm multiplicity, m , inclination, i , angular rates, $\Omega(r)$ and pattern speed, Ω_p , permit calculation of disk surface density, μ , from the dispersion relation (3). We assume stability over the disk and substitute equation (6) into equation (3) giving a quadratic equation for disk surface density. However, since the equation is quadratic, there are two possible values for surface density for a given $(\Omega - \Omega_p)^2$. Consequently, we use Equation (7):

$$\mu_m = \left(\frac{\kappa^2}{\pi G}\right) \left(\frac{r \tan i_m}{m}\right) \left[1 + \frac{m(\Omega - \Omega_p)}{\kappa}\right], \quad (7)$$

where, inside the square bracket, for a declining Ω with respect to radius, the second term in the square bracket is positive for radii inside co-rotation and negative outside. The reverse is true for a rising Ω with radius.

As discussed, NGC4622 has two co-rotation radii which are marked in Figure 5 with vertical dashed lines. From the intersection of these with the rotation curve, the horizontal dashed lines indicate the two pattern speeds, $\Omega_{1,p} = 5.869 \text{ km/s}''$ for CR1 at $21.3''$ and $\Omega_{2,p} = 4.808 \text{ km/s}''$ for CR2 at $36.4''$. These pattern speeds are used in Equation (7) for their neighborhoods inside and outside the neutral zone respectively.

We use the two-fold arms in the calculation of the disk surface density in Equation (7). This pair is strong and leads outside the neutral zone. Inside the neutral zone, the pair is weaker but clearly visible in a two-fold Fourier I band plot as a trailing pair (Figure 6). The inclination of $m = 2$ from $23.1''$ (3.9 kpc) to $48.9''$ (8.23 kpc), is remarkably constant at $i = 7.6^\circ$ even crossing the neutral zone at ~ 3.4 in Figure 7.

The surface density equations above use the angular rates; inside and outside the neutral zone radius where $r = 30''$ and $v = 138$ km/s. Also used are the inner and outer co-rotation radii along with their pattern speed angular rates, CR1, ($\Omega_p = 125$ km/s/21.3'') and CR2 ($\Omega_p = 175$ km/s/36.4'') in their neighborhoods. Finally, two extreme orbital angular rates ($\Omega = 130$ km/s/17.5'' and 330 km/s/52'') are used.

As shown in Figure 8, a declining inner disk surface density is calculated using the Figure 5b curve and the CR1 radius and angular rate. The surface densities are normal, comparable to those in the Milky Way Solar neighborhood. However, using the Figure 5b curve and CR2 radius and angular rate, the outer surface density appears to rise sharply to unusually large values outward through the leading arm region. The arms are smooth over the whole region as seen in Figure 6.

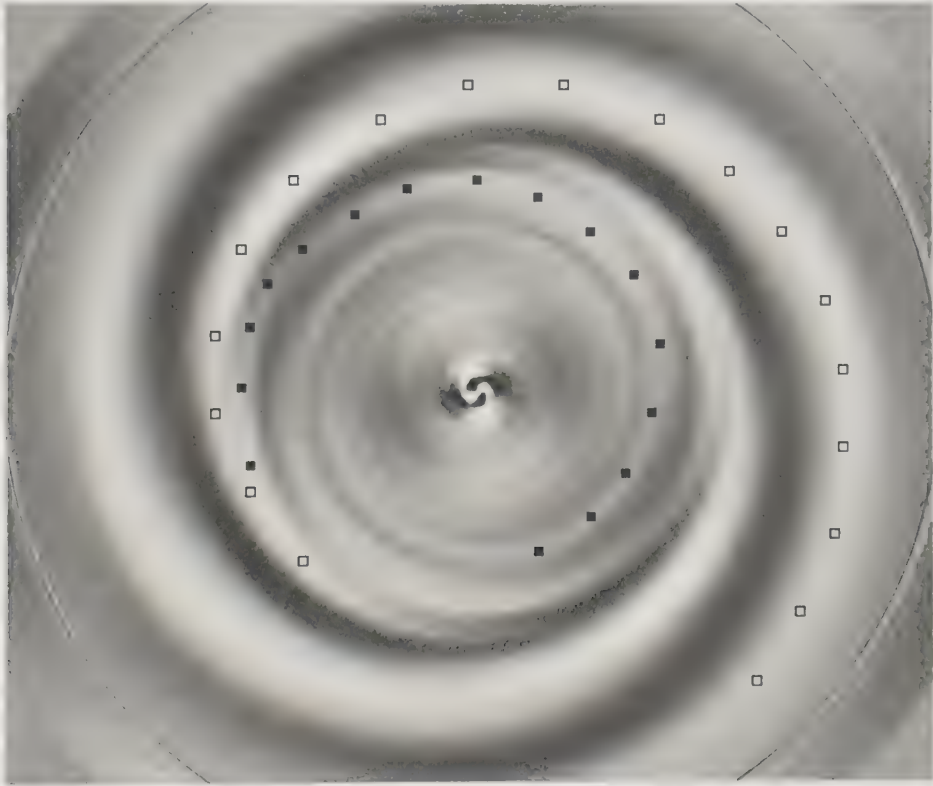


Figure 6. $m=2$ Fourier component of WFPC2 I band image of NGC 4622. North is upper right, and East is upper left. The frame covers $1'.50 \times 1'.43$ stretched to a square to correct for tilt. Outside the neutral zone, one of the leading CW arm pairs is marked with white dots. Inside the neutral zone, one of a clear but weaker pair of trailing CCW arms is marked with black dots. (Byrd et al 2008)

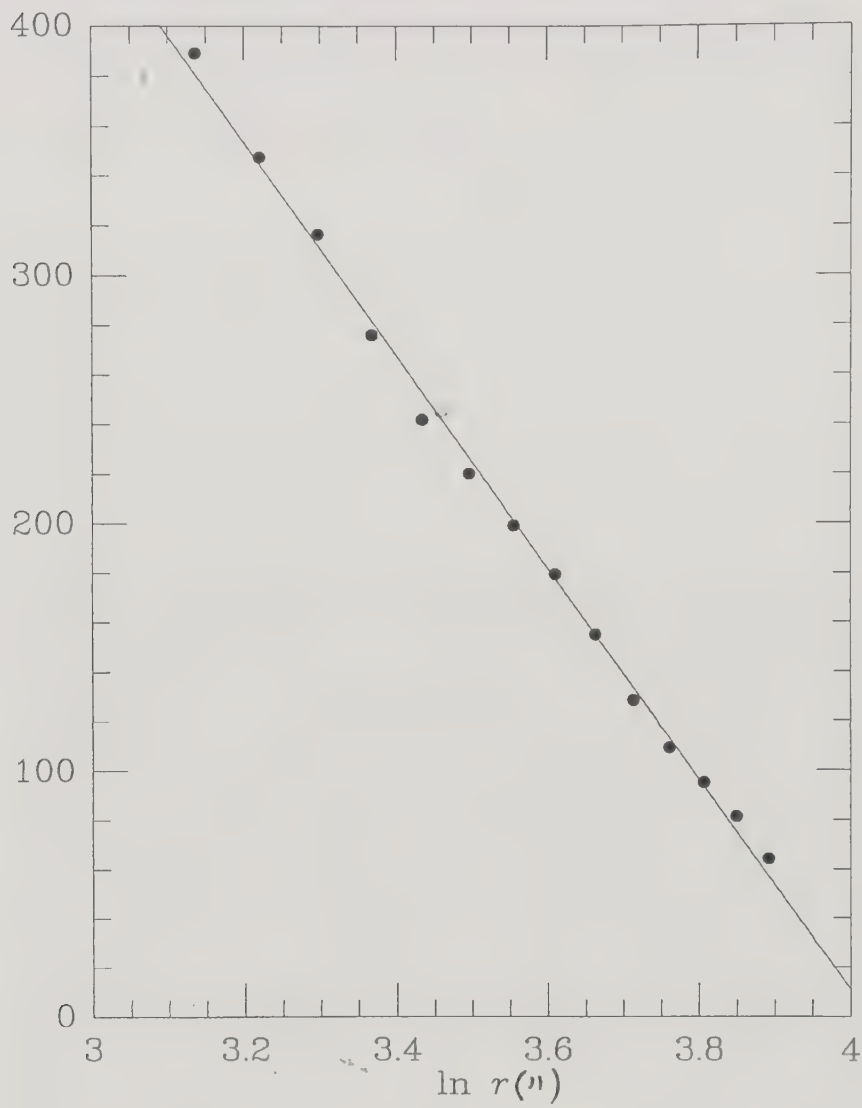


Figure 7 Arm pair position angle in degrees versus $\ln$ radius (")

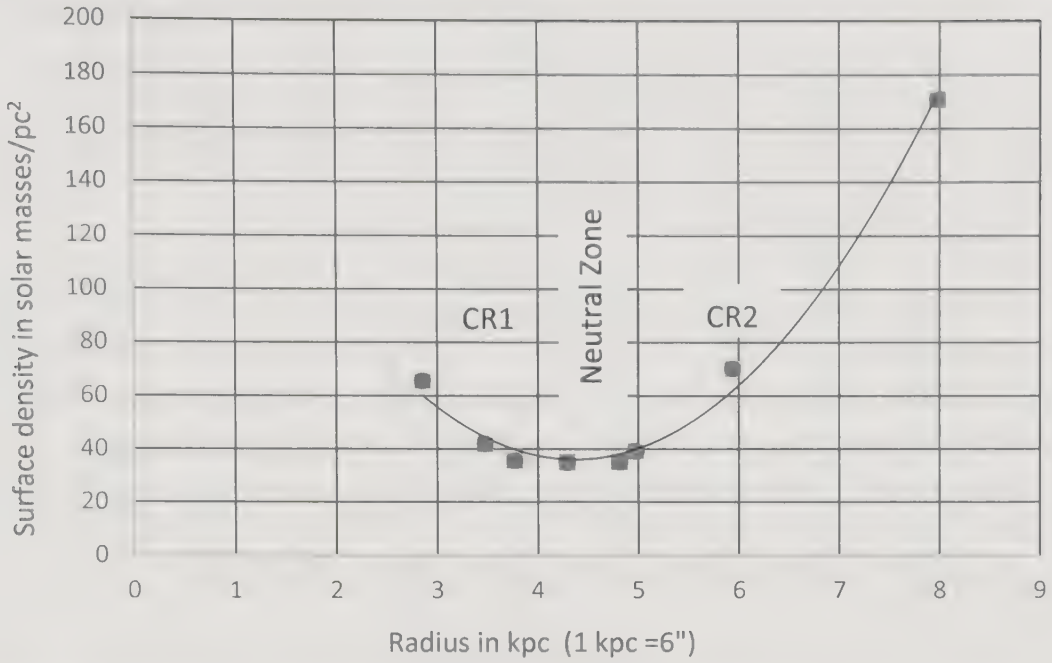


Figure 8 Surface density (solar masses/pc²) versus r (") obtained using: (i) the neutral zone $d\Omega/dr = 0$ and $\Omega = 138$ km/s /30"; (ii) CR1, at $\Omega_p = 125$ km/s/21.3" and CR2 at $\Omega_p = 175$ km/s/36.4"; (iii) Extreme angular rates (130 km/s/17.5") and (330 km/s/52"); and, finally, (iv) inclination angle 7.6° from 3.9 kpc to 8.23 kpc where 5 kpc = 29.7 ".

Conclusions

At first examination NGC4622 has a beautiful spiral pattern composed of two trailing spiral arms outlined by brilliant associations, a prototypical example of a two-armed density wave pattern. As described in Byrd et al (2008 and references), a strong outer pair actually leads relative to the orbit sense and a newly found inner strong single arm trails. It appears that NGC4622 has an unusual density wave pattern with two kinds of arms with each having its co-rotation radius. Both the two kinds of arms wind outward as a smooth log function of radius even across the neutral zone between leading and trailing arms from 3.9 kpc to 8.23 kpc.

As a consequence of NGC 4622's unusual rotation curve, the inner arm trails where the inner angular rate declines with radius. The outer arms lead where the rate rises. Here it is shown the surface density of the disk over both arm regions can be calculated using: (i) the "neutral zone" radius and flat angular rate between leading and trailing arms NGC4622's; (ii) the two co-rotation radii and their associated pattern speeds, (iii) close-in and distant angular rates and radii and finally, (iv) the arms' constant inclination.

The co-rotation radii are accurately determined from color and association switching relative to the stellar arms. Also note that the minimum velocity dispersion for stability is assumed. Hidden arms in the inner and outer disk support the conclusions. No assumption is made about disk mass-to-light ratio. The major uncertainty is the scatter in the rotation V versus radius.

The declining inner disk surface density has normal values comparable to the Milky Way Solar neighborhood. However, the outer surface density appears to rise sharply to unusually large values outward through the leading arm region. Besides its leading and trailing arms, NGC4622's different pattern speeds and anomalously high outer disk surface densities, offer even more puzzles for astronomers. Does NGC4622 have an outer flattened disk of dark matter rather than a halo?

References

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¹ Ω is the symbol for the orbital angular speed of objects revolving about the galaxy center.

PROSPECTIVE LAVA TUBES AT HELLAS PLANITIA

LEVERAGING VOLCANIC FEATURES ON MARS TO PROVIDE CREWED MISSIONS PROTECTION FROM RADIATION

Antonio J. Paris, Evan T. Davies, Laurence Tognetti, & Carly Zahniser

Center for Planetary Science

ABSTRACT

Mars is currently at the center of intense scientific study aimed at potential human colonization. Consequently, there has been increased curiosity in the identification and study of lava tubes for information on the paleohydrological, geomorphological, geological, and potential biological history of Mars, including the prospect of present microbial life on the planet. Lava tubes, furthermore, could serve as *in-situ* habitats for upcoming crewed missions to Mars by providing protection from solar energetic particles, unpredictable high-energy cosmic radiation (i.e., gamma-ray bursts), bombardment of micrometeorites, exposure to dangerous perchlorates due to long-term dust storms, and extreme temperature fluctuations. The purpose of this investigation is to identify and study prospective lava tubes at *Hellas Planitia*, a plain located inside the large impact basin *Hellas* in the southern hemisphere of Mars, through the use of Earth analogue structures. The search for lava tubes at *Hellas Planitia* is primarily due to the low radiation environment at this particular location. Several studies by NASA spacecraft have measured radiation levels in this region at $\sim 342 \mu\text{Sv/day}$, which is considerably less than other regions on the surface of Mars ($\sim 547 \mu\text{Sv/day}$). Notwithstanding, a radiation exposure of $\sim 342 \mu\text{Sv/day}$ is still sizably higher than what human beings in developed nations are annually exposed to on Earth. By analyzing orbital imagery from two cameras onboard NASA's Mars Reconnaissance Orbiter (MRO) – the High-Resolution Imaging Science Experiment (HiRISE) and the Context Camera (CTX) – the search for lava tubes was refined by identifying pit crater chains in the vicinity of *Hadriacus Mons*, an ancient low-relief volcanic mountain along the northeastern edge of *Hellas Planitia*. After surveying 1,500 images from MRO, this investigation has identified three candidate lava tubes in the vicinity of *Hadriacus Mons* as prospective sites for manned exploration. To complement this investigation, moreover, 30 *in-situ* radiation monitoring experiments have been conducted at analog lava tubes located at Mojave, CA, El Malpais, NM, and Flagstaff, AZ. On average, the total amount of solar radiation detected outside the analog lava tubes was approximately $\sim 0.470 \mu\text{Sv/hr}$, while the average inside the analog lava tubes decreased by 82% to $\sim 0.083 \mu\text{Sv/hr}$. We infer, therefore, that the candidate lava tubes identified southwest of *Hadriacus Mons* could

be leveraged to decrease the radiation and to reduce the crew's exposure from $\sim 342 \mu\text{Sv/day}$ to $\sim 61.64 \mu\text{Sv/day}$ (a decrease of $\sim 82\%$). This investigation, therefore, concluded that terrestrial lava tubes can be leveraged for radiation shielding and, accordingly, that the candidate lava tubes on Mars (as well as known lava tubes on the lunar surface) can serve as natural radiation shelters and habitats for a prospective crewed mission to the planet.

THE RADIATION ENVIRONMENT ON MARS

EARTH'S MAGNETIC FIELD PROTECTS US from harmful solar and Galactic cosmic radiation. Though astronauts in low-earth orbit are more exposed to radiation than humans on the ground, they are still protected by Earth's magnetosphere. Outside our magnetosphere, however, radiation is more problematic. Research studies of exposure to various strengths and doses of radiation provide strong evidence that degenerative diseases and/or cancer are to be expected from too much exposure to solar energetic particles and/or galactic cosmic rays.¹ Galactic cosmic radiation contains highly ionizing heavy ions that have large penetration power in tissue and that may produce extremely large doses, leading to early radiation sickness or death if adequate shelter is not provided.² During the Apollo program, for illustration, astronauts on the moon reported headaches, reported seeing flashes of light, and experienced painful cataracts.³ These symptoms, known as Cosmic Ray Visual Phenomena, were due to radiation from cosmic rays interacting with matter and depositing its energy directly in the eyes of the astronaut.⁴ The Apollo missions, however, were comparatively short, and they cannot be likened to a multi-year presence on the surface of Mars.

Approximately 4.2 billion years ago, due to either rapid cooling in its central core or a massive impact from an asteroid or comet, the magnetic dynamo effect on Mars stopped, and its magnetosphere weakened dramatically.⁵ As a result, over the course of the next 500 million years, the Martian atmosphere was gradually stripped away by the solar wind. Between the loss of its magnetic field and its atmosphere, the surface of Mars is now exposed to much higher levels of solar and cosmic radiation than Earth. In addition to regular exposure to solar energetic particles and galactic cosmic rays, the planet receives intermittent harmful blasts that occur from strong solar flares, as well as the bombardment of meteors.⁴ A crewed mission to the surface of Mars, consequently, will introduce the

crew and its critical life-support equipment to an environment outside a much-needed magnetosphere. They will be at risk of absorbing sudden fatal radiation doses, as well as assuredly suffering cellular and DNA damage from chronic high background radiation, which will lead to cancer. Additionally, there is a risk of an unpredictable cosmic ray burst or a meteor shower capable of critically damaging the crew's life-support equipment.¹

Numerous investigations by NASA have established that the surface of Mars receives a varying amount of radiation. The difference is largely due to where the solar wind interacts with electrically charged particles in the Martian upper atmosphere and the particular topographic elevation on the planet. The Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft, for illustration, detected the interaction of the solar wind with electrically charged particles of the Martian atmosphere.⁶ Atoms in the upper atmosphere became electrically charged ions after being energized by solar and cosmic radiation. Because they are electrically charged, these ions interact with the magnetic and electric forces of the solar wind, a thin stream of electrically conducting gas ejected from the surface of the Sun.⁴ As explained in Figure 1, the lines represent the paths of individual ions, and the colors represent their energy, E , measured in electron volts (eV). The MAVEN investigation concluded that the northernmost polar plume contains the most energetic ions, ranging as high as $\sim 20,000$ E (eV) – with the surface of the planet's northern polar region receiving approximately $\sim 10,000$ to $\sim 1,000$ E (eV), the southern polar region receiving $\sim 1,000$ to ~ 100 E (eV), and the mid-latitudes receiving the lowest at ~ 300 to ~ 10 E (eV).⁷

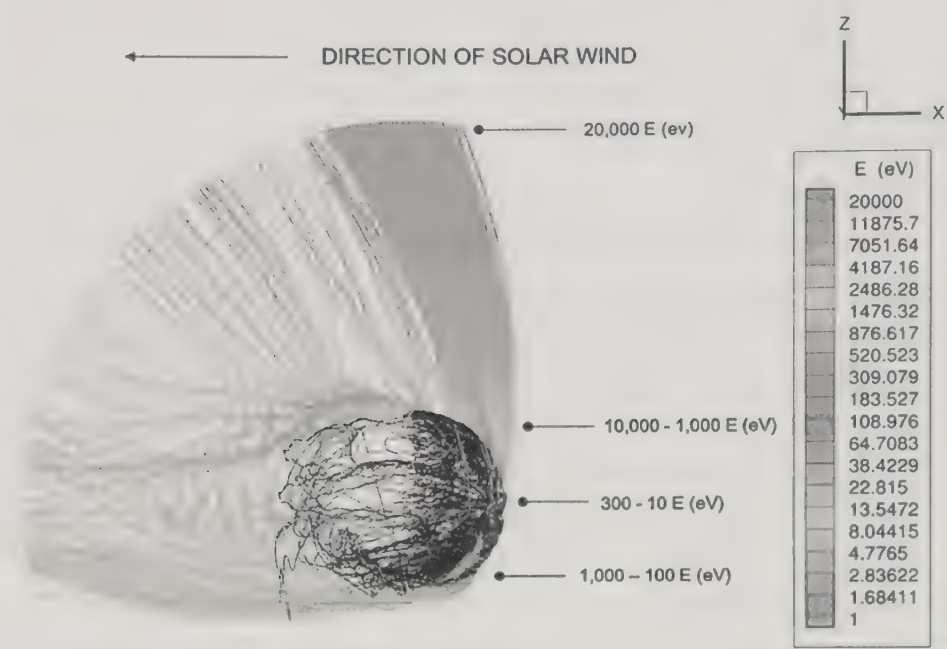


Figure 1: MAVEN Investigation of the Solar Wind on Mars. (Source: NASA)

Similarly, the NASA Mars Odyssey spacecraft was equipped with a special instrument called the Martian Radiation Experiment (MARIE), which was also designed to measure the radiation environment on Mars.⁸ Over the course of 18 months, MARIE detected ongoing levels of radiation that were considerably higher than what astronauts experience on the International Space Station (~200 $\mu\text{Sv/day}$).⁵ At high topographic elevations, MARIE detected radiation levels at ~547 $\mu\text{Sv/day}$, which equates to ~200,000 $\mu\text{Sv/year}$ (Figure 2). Although there are no immediate symptoms while being exposed to ~547 $\mu\text{Sv/day}$, exposure to these levels of radiation for one year is four times the maximum annual allowable exposure for U.S. radiation workers (50,000 $\mu\text{Sv/year}$), which can cause radiation sickness.⁹ In contrast, the radiation levels at lower elevations were measure at ~273 $\mu\text{Sv/day}$, because those areas have more atmosphere above them to block out a considerable amount of the radiation.¹⁰ For comparison, humans in developed nations are exposed to, on average, ~6,200 $\mu\text{Sv/year}$.¹¹

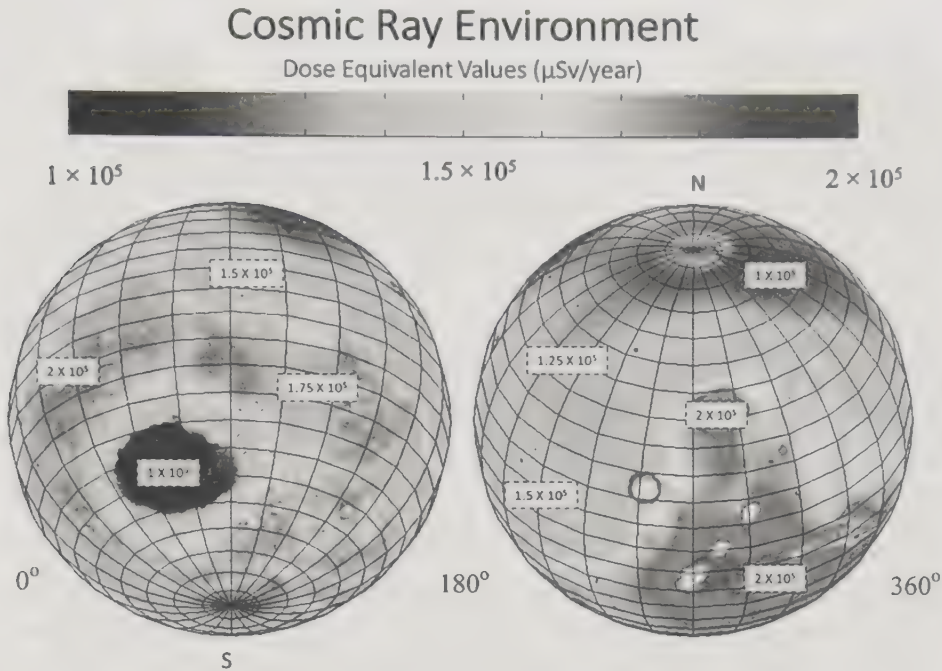


Figure 2: MARIE Investigation of the Cosmic Radiation Environment on Mars.
(Source: NASA)

In September 2017, strong energetic particles from a coronal mass ejection were detected both in Mars orbit and on the surface (Figure 3).¹² In orbit, MAVEN detected energetic particles as high as 220 million E (eV), which produced radiation levels on the surface more than double any previously measured by Curiosity's Radiation Assessment Detector (RAD).¹³ RAD is an energetic particle detector capable of measuring all charged particles that contribute to the radiation health risks that future crewed missions to Mars will face.¹⁴ At the time of the coronal mass ejection, Curiosity was positioned inside Gale Crater at an elevation of ~4,500 m. As cited previously, a lower elevation on Mars allows for additional atmosphere above the rover, which aids in blocking out a considerable amount of radiation. At Gale Crater, the normal background radiation measured by RAD prior to the coronal mass ejection was ~220-270 $\mu\text{Sv}/\text{day}$, which is similar to what MARIE detected (~273 $\mu\text{Sv}/\text{day}$). However, during the coronal mass ejection, RAD detected radiation levels at ~600 $\mu\text{Sv}/\text{day}$ – over twice the normal background radiation at Gale Crater (Figure 3).¹² While studies have shown that the human body can withstand a single dose of up to 2,000,000 μSv without permanent damage,⁴

prolonged exposure to strong energetic particles will lead to health complications – including acute radiation sickness (nausea, vomiting, weakness, headaches, purpura, hemorrhage, infections, diarrhea, leukopenia), genetic damage, and possibly death. Moreover, exposure to more than 5,000,000 μSv would kill half of those exposed within a month, and 10,000,000 μSv would be fatal within days.¹⁵

The data from MAVEN, MARIE, and RAD show that the solar wind and other violent solar activity, such as solar flares and coronal mass ejections, continue to strip away the Martian atmosphere – but more importantly, they make the northern latitudes less desirable for human exploration. The data indicate, moreover, that a crewed mission should more prudently be placed along the mid-to-southern latitude range – where there is minimized ionic activity from the solar wind (i.e., *Hellas Planitia*). Furthermore, the data suggest that the crew should be placed at lower elevations along the surface of Mars (again, *Hellas Planitia*), with its thicker atmosphere, which will help to block out the radiation by a factor of two. Additionally, a crewed mission on Mars should be effectuated during a solar minimum (the period of least solar activity in the 11-year solar cycle of the Sun) to ensure that exposure to radiation due to a solar flare and/or coronal mass ejection is minimized.¹⁶

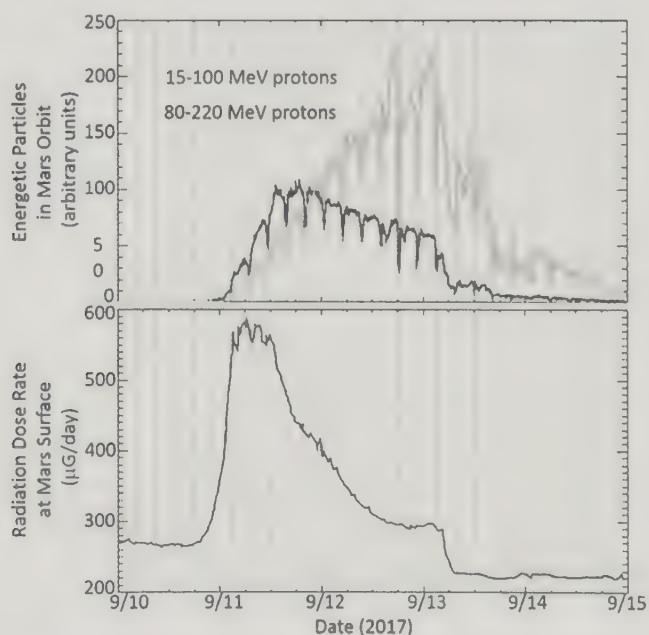


Figure 3: Radiation data collected by MAVEN and RAD during the September 2017 solar storm. (Source: NASA)

ANCIENT VOLCANISM ON MARS

Volcanic activity has played an extensive role in the geologic development of Mars. Planetary scientists have acknowledged since the Mariner 9 mission in 1972 that volcanic topographies cover great portions of the Martian surface. These geological features include widespread lava flows, lava plains, and the largest known volcanic peaks in the solar system, including the highest, Olympus Mons.¹⁷ Volcanic features on Mars range in age from the Noachian (> 3.7 billion years) to the late Amazonian (< 500 million years) eras, demonstrating that Mars was volcanically active early in its history.¹⁸ Mars, moreover, is a differentiated terrestrial planet that formed from analogous chondritic materials.¹⁹ Many of the same magmatic processes that occurred on Earth, for comparison, also took place on Mars. The two planets are sufficiently comparable compositionally that similar names can be applied to their igneous rocks and minerals.²⁰ The shape and size of volcanoes on Mars, though, were largely dependent on a set of environmental conditions and properties dissimilar to Earth. Lesser atmospheric pressure altered the scattering of ejected material, a higher eruption rate allowed for the lava on the surface to pile up higher, and lower gravity facilitated wider dispersion.²¹ Consequently, volcanoes and lava tubes on Mars are more than twice as large as their terrestrial analogues.

THE FORMATION OF LAVA TUBES

Lava is molten rock that is ejected by a volcano during an eruption. The molten rock on Mars was formed in the interior of the planet in high temperatures produced by geothermal energy. When the lava first erupts from a volcanic vent, it is in a liquid state, typically at temperatures ranging from 1,292° to 2,192°F.²² A lava flow, in contrast, is an outburst of lava that moves during a non-explosive effusive eruption. When the lava flow stops moving, it cools and hardens to form igneous rock. While lava can be up to 100,000 times more viscous than water, it can flow for a large distance before abating and solidifying.²³ Lava flows can occasionally form lava tubes – natural subsurface caves or caverns – which appear to form because of rapid lava flow. Lava tubes, which are usually made from extremely fluid pahoehoe lava, typically form when the exterior surface of lava channels cools more rapidly and forms a strong crust over the subsurface lava.²⁴ The lava flow ultimately stops and drains out of the tube, leaving a conduit-

shaped void located several feet underneath the surface (Figure 4). As we discussed above, as gravity on Mars is 37% of that on Earth, lava flow, and subsequently lava tubes on Mars, are generally much larger than those found on Earth.²⁵



Figure 4: Prof. Antonio Paris, the Principal Investigator, conducting research at the El Calderon lava tubes in El Mapais, New Mexico.

IDENTIFYING PIT CRATER CHAINS AND LAVA TUBES

Lava tubes below the surface of Mars, as well as those below the lunar surface, can be identified by locating pit craters in the vicinity of known ancient lava flows. A pit crater is a circular or elliptical depression shaped by the collapsing or sinking of the surface lying above a void or hollow cavity, rather than by the eruption of a lava vent or volcano. Pit craters generally lack a raised rim, uplifting, ejecta blankets associated with impact craters, or radial patterns of lava flows discharging downslope from volcanic calderas.²⁶ There are generally two types of pit craters – atypical and bowl-shaped. Atypical pit craters exhibit a distinctive set of morphologies and characteristics that set them apart from the commonly observed bowl-shaped pit craters. Instead of bowls, the interior of atypical pit craters is cylindrical or bell-shaped with vertical to overhanging walls

that extend down to their floors without forming talus slopes.²⁷ In some instances, atypical pit craters show evidence of vents, fissures, and caverns/caves that could be intact.

Pit craters have been discovered on Earth, Mars, as well as on the various moons in our solar system (including our Moon).²⁸ They are generally located in a series of ranged or offset chains; and in these instances, they are referred to as pit crater chains (Figure 5). When adjacent walls between pits in a pit crater chain collapse, they become troughs.²⁹ A commonly invoked hypothesis to explain these troughs is that they are collapsed lava tubes, essentially tunnels formed underground by rivers of lava.³⁰

Through the use of spacecraft imagery, lava tubes on Earth, Mars and the Moon can be visually detected in two ways. The first method is by recognizing troughs or rilles, which, as mentioned previously, are believed to be the remains of collapsed lava tubes. The second method is by pinpointing “skylights” – dark, nearly rounded features that are hypothesized as entrances to lava tubes.³¹ At this point, light from the Sun enters into the permanent darkness of the lava tube from above, forming a skylight.²⁰ Many lava tubes on Earth, for instance, have been identified through the discovery of skylights (Figure 5). As is the case on Earth, access to uncollapsed sections of lava tubes on Mars is available by entering through a skylight, at the end of the trough or rille where a cave/cavern could lead into the lava tube, or by drilling or blasting through the roof of a lava tube.³² The Lunar Reconnaissance Orbiter, moreover, has imaged over 200 pits craters on the lunar surface. Many of these lunar pits craters show skylights into subsurface voids or caverns, ranging in diameter from about 5m to more than 900m, although some of these are likely to be post-flow features rather than volcanic skylights.³³ Moreover, there is observational evidence from orbiting spacecraft to infer there are lava tubes along the *Marius Hills*, *Hadley Rille* and *Mare Serenitatis* regions of the Moon.³⁴ While the lunar surface varies in temperature from -180 C to +100 C, the interior of these lunar lava tubes could remain at a constant -20 C. Therefore, lava tubes on the Moon (as well as on Mars), once sealed off, could be warmed up and pressurized with a breathable atmosphere.³⁵



Figure 5: Similarities between a pit crater chain and pit crater “skylight” at El Mapais, NM (top image) and South of Arsia Mons on Mars (bottom image).
(Source: NASA, Processing: Center for Planetary Science)

**HELLAS PLANITIA:
PROSPECTIVE SITE FOR MANNED EXPLORATION**

Hellas Planitia is a large meteorite impact basin located at 42° 42’ S and 70° 00’ E, in the southern hemisphere of Mars, in the *Hellas* and *Noachis* quadrangle.³⁶ The impact basin is thought to have been formed during the Late Heavy Bombardment period of the Solar System, approximately 4.1 to 3.8 billion years ago, when a large asteroid hit the surface. It is 2,300 km in diameter, and it is one of the largest known impact craters in the solar system (Figure 6).³⁷ Measurements made by the Mars Orbiter Laser Altimeter (MOLA) instrument onboard the Mars Global Surveyor spacecraft indicate that the basin floor is ~7,152 m deep – making *Hellas Planitia* one of the bottom-most geographic elevations on the planet.³⁸ At this depth, consequently, *Hellas Planitia* has one the lowest ongoing radiation levels on Mars.

According to data from NASA’s MARIE experiment, radiation levels at *Hellas Planitia* have been measured at $\sim 1 \times 10^5 \mu\text{Sv/year}$, as opposed to the higher topographic elevations on Mars, which were measured at $\sim 2 \times 10^5 \mu\text{Sv/year}$ (Figure 6).⁸ The depth of the basin, moreover, is below the standard topographic datum of Mars, which explains the atmospheric pressure at the bottom of the basin: 12.4 mbar during the northern summer. This is 103% higher than the pressure at the topographical datum (6.1 mbar) and above the triple point of water, indicating that a liquid phase might be present under certain conditions of temperature, pressure, and dissolved salt content.³⁹ These conditions could provide the crew on Mars the opportunity to identify and study lava tubes in this region for information on the geological, paleohydrological, overall geomorphological, and potential biological history of the planet. While there is as of yet no evidence for this, an exciting notion is that, as with extremophile environments on Earth, these locations may serve as habitats for possible microbial life on Mars.⁴⁰

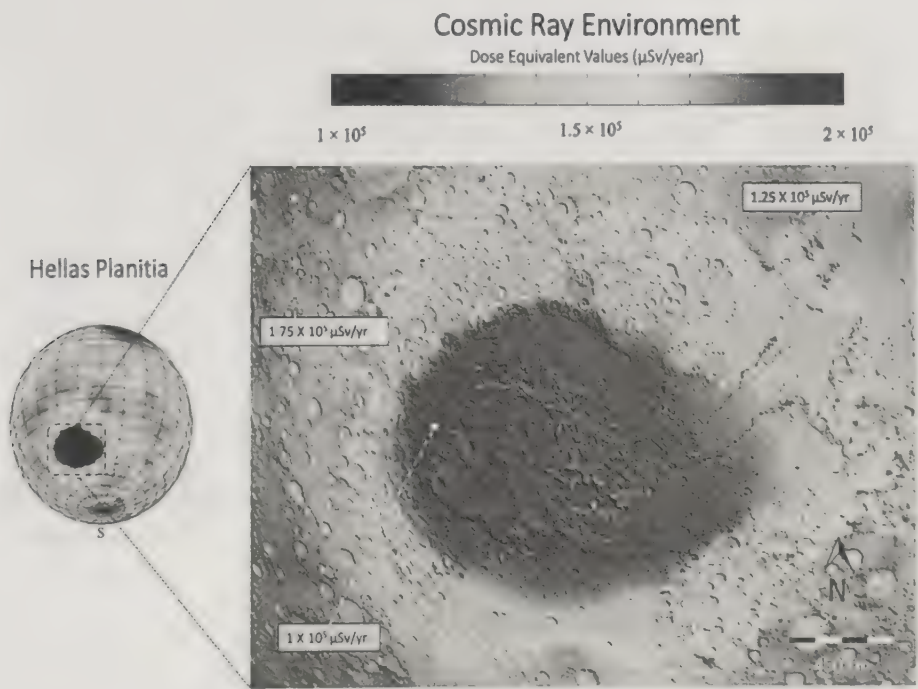


Figure 6: An expanded view of the radiation environment at Hellas Planitia.
(Source: Center for Planetary Science)

HADRIACUS MONS REGION: PROSPECTIVE LAVA TUBES FOR MANNED EXPLORATION

Hadriacus Mons is an ancient, low-relief volcanic mountain located along the northeastern edge of *Hellas* (Figure 7). The volcano has a diameter of 450 kilometers, and its features differ from other volcanos such as Olympus Mons and the others in Tharsis and Elysium. *Hadriacus*'s low slopes, wide structure, and heavily scored flanks suggest that it is made of eroded materials.⁴¹ Planetary scientists classify this volcanic debris as pyroclastic, from the Greek meaning "fire-broken." The large extent of volcanic deposits and the caldera size, moreover, leads some planetary scientists to infer that these geological topographies were the result of an explosive event caused by a contact between erupting magma and groundwater.⁴²

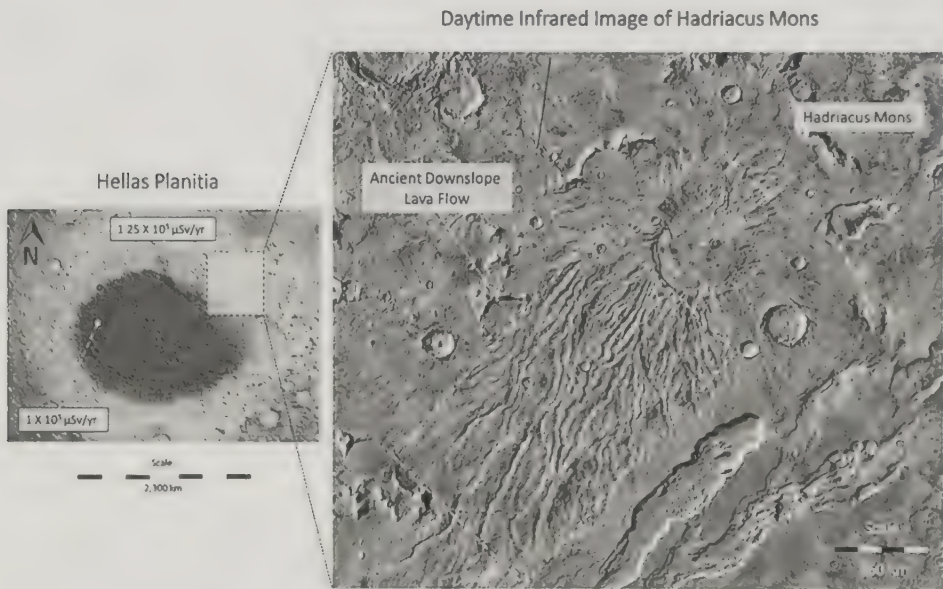


Figure 7: An expanded view of Hadriacus Mons along the edge of Hellas Planitia
(Source: NASA and Center for Planetary Science)

The low radiation levels along the lava flows in this region that extends from *Hadriacus Mons* into *Hellas Planitia* make the location a prime candidate for human exploration. According to data from NASA's MARIE experiment, radiation levels in this region have been measured at $\sim 1.25 \times 10^5 \mu\text{Sv/year}$ ($\sim 342.46 \mu\text{Sv/day}$), which, as previously mentioned,

is considerably lower than the higher topographic elevations on Mars, which were measured at $\sim 2 \times 10^5 \mu\text{Sv/year}$. Notwithstanding, a radiation exposure of $1.25 \times 10^5 \mu\text{Sv/year}$ is still sizably higher than what human beings in developed nations are annually exposed to on Earth. The lava tubes near *Hadriacus Mons*, consequently, could be used as natural radiation shelters and habitats for a crewed mission to the planet. These natural caverns have roofs estimated to be tens of meters thick, which would provide the crew protection from not only exposure to too much radiation, but also the bombardment of micrometeorites, exposure to dangerous soil perchlorates due to long-term dust storms, and extreme temperature fluctuations.⁴³ Moreover, although the exact conditions of the interior of Martian lava tubes will remain unknown until they are actually explored, planetary scientist are of the consensus that they represent prime locations for direct observation of pristine Martian bedrock, where keys critical to understanding the natural history of this planet will be found.³³

The NASA HiRISE and CTX data used in this study were available through NASA's Planetary Data System (PDS). MRO CTX observes Mars's surface at ~ 6 m/pixel in swaths of 30 km across and up to ~ 160 km in length. MRO also observes the Martian surface earlier in the day; thus, more pit craters can be observed with partially sunlit floors.³² A partially sunlit floor allows planetary scientists to identify specific pit crater characteristics such as skylights, individual boulders, dusty, or rocky surface textures, overhanging rims, wall and floor morphologies, and bedrock stratification.³²

An analysis of 1,500 HiRISE and CTX images of the *Hellas Planitia* basin uncovered several volcanic features southwest of *Hadriacus Mons*, which were subsequently identified as candidate lava tubes (Figure 8). The first candidate lava tube identified in this study is located southwest of *Hadriacus Mons* in the *Dao Vallis* region at latitude -36.961° and longitude 87.841°E (MRO CTX Catalog: J11_049132_1423_XN_37S272W). The $\sim 4,500$ -meter collapsed lava pit (Figure 8a), which is positioned between two partially collapsed sinuous pit crater chains, depicts two surface areas that have not collapsed (Figure 8a and 8b). Imagery analysis indicates the area of the northern uncollapsed surface is ~ 600 meters long and ~ 300 meters wide (Figure 8a), and that the area of the southern uncollapsed surface is ~ 900 meters long and ~ 600 meters wide (Figure 8b). Further

analysis of the ~4,500-meter collapsed lava pit with its contrast range limited to low-end radiance values indicate that the pit crater walls encompassing both uncollapsed areas are structurally intact – ruling out a lava bridge – indicating that a lava tube below the surface is plausible, since these parts of the pit crater chain have not collapsed.

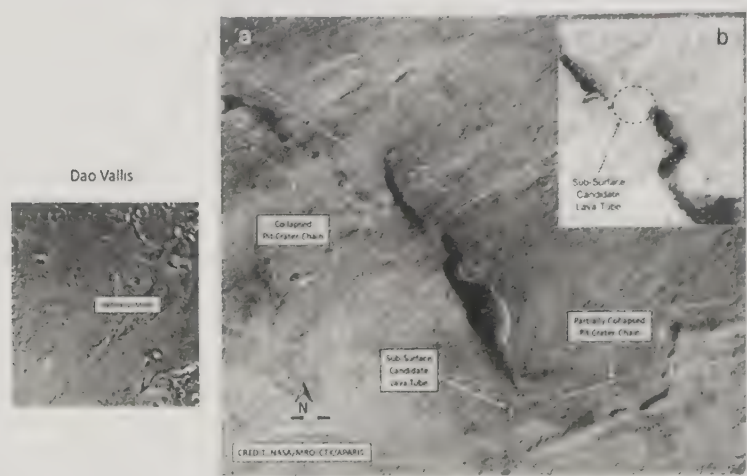


Figure 8: Candidate lava tubes south of Hadriacus Mons. (Credit: Center for Planetary Science)

The second candidate lava tube identified in this study is located south of *Hadriacus Mons* in the *Dao* and *Niger* valleys region at latitude -33.256° and longitude 93.980°E (MRO CTX Catalog: CTX: P13_006237_1475_XN_32S266W). An analysis of the CTX imagery depicts an atypical pit crater with a diameter of ~700 meters positioned between two sinuous chains of partially collapsed elliptical bowl-shaped pit craters (Figure 9a). The same atypical pit crater with its contrast range limited to low-end radiance values depicts the presence of a possible overhanging rim or shoulder along the northern section, which could be the entrance to a lava tube (Figure 9b). As mentioned previously, the leading accepted hypothesis is that since the pit crater chains East and West of this atypical pit crater have not fully collapsed, then a lava tube could exist below the surface.

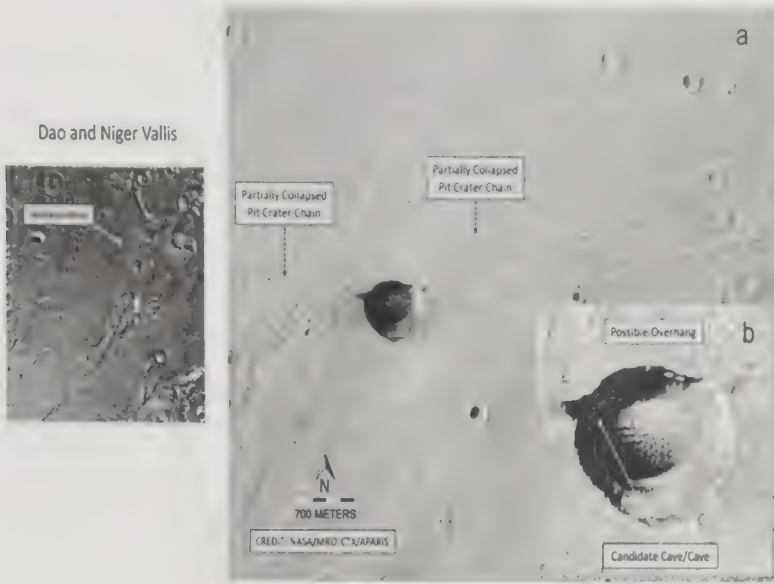


Figure 9: Candidate lava tubes south of Hadriacus Mons. (Credit: Center for Planetary Science)

The third candidate lava tube identified in this study is located southwest of *Hadriacus Mons* in the *Dao Vallis* region at latitude -36.870° and longitude 89.498°E (MRO CTX Catalog: F03_036987_1432_XN_36S270W). The ~ 25 -meter collapsed pit, which appears to indicate the entrance to a candidate cavern and/or cave, is preceded by a partially collapsed trough (Figure 10a). The collapsed trough is sinuous, and, as previously cited, it could be associated with the presence of a lava tube below the surface. The same collapsed pit with its contrast range limited to low-end radiance values depicts the presence of boulders that more than likely arose from the collapse of the western wall section, which could be the entrance to a lava tube (Figure 10b). The region of the candidate lava tube, moreover, is characterized by numerous sinuous collapsed pit crater chains ranging in size – providing further evidence that one or more lava tubes could exist below the surface. Interestingly, this proposed lava tube is analogous to Giant Ice Cave in El Mapais, NM (Figure 11), which is also characterized by a partially collapsed sinuous trough that leads into the entrance of a lava tube.

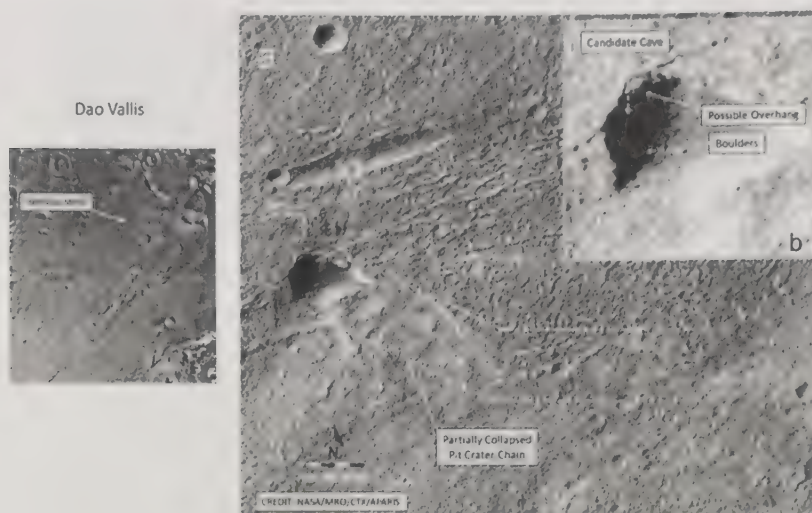


Figure 10: Candidate lava tubes south of Hadriacus Mons. (Credit: Center for Planetary Science)

RADIATION EXPERIMENTS AT TERRESTRIAL ANALOG LAVA TUBES

To ascertain whether lava tubes on Mars (or correspondingly the lunar surface) could be used by surface crews to reduce exposure from solar or cosmic radiation, we conducted 30 analog radiation experiments. The experiments were conducted during solar noon at terrestrial lava tubes (Figure 11) located at Mojave, CA (Aiken), El Mapais, NM (Big Skylight, Giant Ice Cave, and Junction Cave) and Flagstaff, AZ. (Lava River Cave). Because radiation from the sun strikes the surface of Earth at different angles, conducting the experiments at solar noon (when the sun is directly overhead) allowed the surface area where the experiments were conducted to receive the most electromagnetic energy from the sun possible.⁴⁴ Furthermore, a sun at 90° above the surface of each lava tube prevented the radiation from becoming too scattered and diffused.

The Geiger counter for this experiment was equipped with a halogen-quenched, long thin cylindrical Geiger-Mueller tube capable of detecting Gamma and X-rays (ionizing radiation) down to 10 keV thru the window, 40 keV minimum through the case, and with a Gamma sensitivity of 10,000 $\mu\text{Sv/hr}$. Although Earth's atmosphere and magnetic field protect us from most ionizing radiation from the Sun, streams of ionizing radiation still reach the surface of Earth. Occasionally, during a solar particle event,

larger amounts of ionizing radiation strike the surface of the Earth, which can also be detected by the Geiger counter.

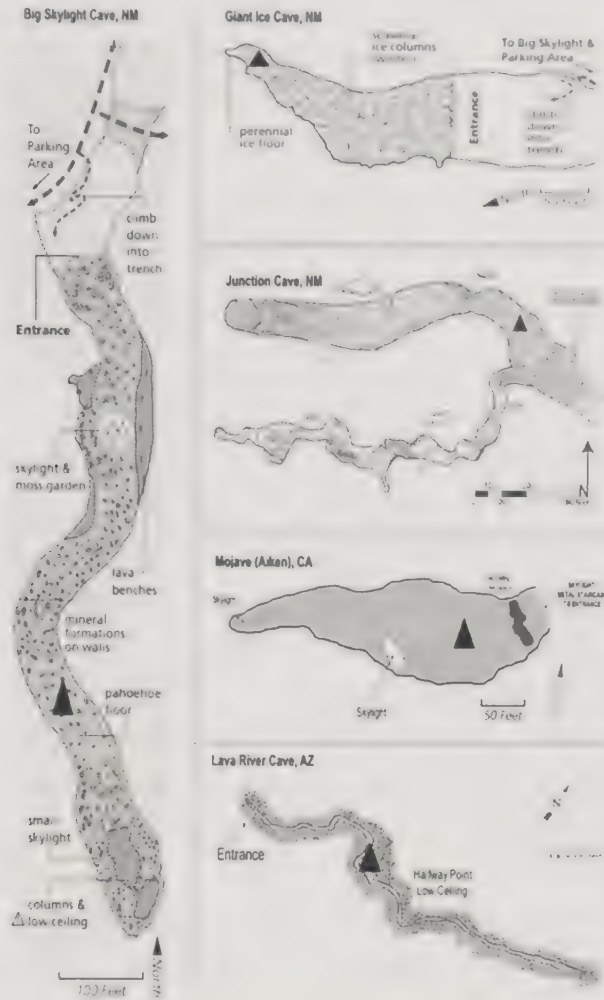


Figure 11: Lava tube maps and the interior locations (black triangle) where each radiation experiment was conducted.

(Map Sources: Mojave lava tube sketched by Prof. Antonio Paris, others National Park Service)

Preceding each experiment, the device was turned on for a minimum of one hour to establish a baseline reading. The experiment was then conducted in two parts – measuring the amount of solar radiation outside the lava tube and then comparing it with the amount of solar radiation measured inside the lava tube. In total, six one-hour readings were completed for each lava tube (three exterior and three interior) for a total of

30 observation hours (Table 1). On average, the total amount of radiation detected during solar noon on the exterior of all five lava tubes was ~0.471 $\mu\text{Sv/hr}$ (V_1) while the average radiation detected inside the lava tubes was ~0.083 $\mu\text{Sv/hr}$ (V_2). Furthermore, during the experiments, we observed a significant drop in temperature (Table 1) inside the terrestrial lava tubes, which likewise would be the case for lavas tubes on Mars.

Analog Site	Avg Surface Reading $\mu\text{Sv/hr}$	Average Interior Reading $\mu\text{Sv/hr}$	Avg Surface Temperature - C	Average Interior Temperature - C
Mojave Aiken - California	0.468	0.088	12	9
El Malpais - Big Skylight - New Mexico	0.501	0.062	20	13
El Malpais - Giant Ice Cave - New Mexico	0.434	0.098	18	10
El Malpais - Junction Cave - New Mexico	0.458	0.078	17	11
Lava River Cave - Arizona	0.492	0.089	25	12
Average	0.4706	0.083	18.4	11

Table 1: Average amount of radiation ($\mu\text{Sv/hr}$) measured at five terrestrial lava tubes.
(Source: The Center for Planetary Science)

When we applied the percentage change equation (Figure 12), the results of the radiation experiment showed that, on average, the amount of radiation (A_I) in the interior of the analog lava tubes decreased by an average of 82%. We can infer, therefore, that the candidate lava tubes identified southwest of *Hadriacus Mons* could be leveraged to decrease the radiation by ~82% and, accordingly, to reduce the crew’s exposure from ~342.46 $\mu\text{Sv/day}$ to ~61.64 $\mu\text{Sv/day}$.

$$A_I = \frac{|\Delta V|}{|V_1|} \times 100 = A_I = \frac{|V_2 - V_1|}{|V_1|} \times 100$$
$$A_I = \frac{|0.083 \mu\text{Sv/hr} - 0.470 \mu\text{Sv/hr}|}{|0.470 \mu\text{Sv/hr}|} \times 100 =$$
$$= 82.34\% \text{ (decrease in radiation)}$$

Figure 12: Percentage change equation for radiation reduction inside analog lava tubes.

CONCLUSION

An analysis of HiRISE and CTX imagery of the *Hellas Planitia* basin, specifically southwest of *Hadriacus Mons*, identified pit crater chains consistent with known lava tube morphology. Although the internal structural conditions of the candidate lava tubes remain largely unknown, a close examination of the satellite surface imagery suggests that sections of the pit crater chains have not collapsed, and therefore that lava tubes below the surface could be internally intact. Furthermore, the candidate lava tubes identified in this investigation are positioned in a region of Mars that regularly has lower radiation exposure than other regions on the planet. Though a background radiation environment of $\sim 342.46 \mu\text{Sv/day}$ is still significantly high, the terrestrial analog experiments conducted at Mojave, CA, El Malpais, NM, and Flagstaff, AZ concluded the lava tubes southwest of *Hadriacus Mons* could reduce the crew's exposure to radiation to $\sim 61.64 \mu\text{Sv/day}$. The results of this investigation, therefore, indicate that the proposed lava tubes southwest of *Hadriacus Mons* can and should be utilized to serve as natural shelters for a crewed mission to the planet. These natural caverns would provide the crew protection from excessive radiation exposure, shelter them from the bombardment of micrometeorites, reduce their exposure to hazardous perchlorates in the Martian regolith, and provide them a degree of protection from extreme temperature fluctuations. The candidate lava tubes, moreover, can serve as important locations for direct observation and study of Martian geology and geomorphology, as well as potentially uncovering any evidence for the development of microbial life early in the natural history of Mars.

BIOS

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Background Material

Lead in Drinking Water in the District of Columbia, 2000 - 2004: A Case Study of Public Health Risk and Abatement

Tee L. Guidotti, MD

Abstract

In 2001 following a change in disinfection agent in anticipation of the EPA Disinfection Byproduct Rule, average lead levels began rising in drinking water in Washington, DC, initially at a slow rate. By 2002 the DC Water and Sewer Authority (WASA) was found to have exceeded the EPA lead action level, requiring compliance with a series of measures under the Lead and Copper Rule. In 2004, the issue became a public concern as articles in the Washington, DC, press appeared. The water chemistry problem was resolved in late 2004 through the application of orthophosphate. The risk management options utilized by WASA included public education, provision of water filters, flushing, support for monitoring blood lead levels, monitoring of lead in water, replacement of lead service lines, and obtaining access to public health and risk management services. The experience from the incident cannot be used to assess the contribution of lead in drinking water to blood lead levels, because there were numerous interventions likely to have mitigated any effect. This case study describes several lessons learned in risk communication applied to water issues.

Introduction

IN 2004 NEWS ABOUT ELEVATED LEVELS of lead in the drinking water in some homes caused considerable concern to residents of the District of Columbia (DC). (Guidotti *et al.* 2008) The responsible utility, the DC Water and Sewer Authority (WASA), was suddenly faced with a practical environmental risk management problem of enormous proportions, notwithstanding the limited public health significance of the event. The unintended consequences of these interventions played out over several years and continue today, in 2009.

This case study documents the origins of the problem and describes the sequence of events that followed, providing an accurate

chronology and insights into policy issues as they arose. Fundamental issues relating to the regulation and management of drinking water quality came to light during this experience. Most of these issues were national in scope but were first and most acutely felt in Washington, DC, as a result of the incident. These key issues will be highlighted throughout the case study. Supplementing these essential or key issues are numerous secondary issues, which will be noted as they arise. This case study covers 2004.

Background

The drinking water distribution system of Washington is similar to that of other major cities such as Philadelphia and New York City. Water is essentially free of lead when collected, disinfected, finished, supplied to the distribution system and delivered to the water mains serving a street or neighborhood. Lead enters drinking water by migrating from lead-containing surfaces distal to the water main. The most important source, where it is present, is dissolved lead from the lumen of lead service lines, which deliver water from the main to the tap. Until approximately 1950, but with many exceptions, lead was the material of choice for service lines to single-family houses because it is malleable and repaired easily. Subsequently, lead service lines were replaced in new construction and for rehabilitated houses by copper or polyvinyl chloride. A further complication in the District of Columbia not present in other cities is that the service line to the house is divided at the property line: the proximal part is the public portion of the service line, owned by the water utility, and the distal part belongs to the property and therefore the responsibility of the homeowner. (Figure 1) In New York and Philadelphia the entire service line is deemed to be private property.

At the time events unfolded in 2000 and 2001, there were approximately 100,000 metered customers in the District of Columbia, of which an estimated 23,000 had service lines connecting the main line to the house that were made of lead (Nakamura 2004b). Lead was a standard material for service lines in the early twentieth century, though modern home construction uses copper or plastic piping. Single-family homes built before about 1950 often, but not invariably, originally had lead service lines. Some homes have had their lines replaced and some were originally installed using other materials, even in the pre-World War II

era. The qualities of malleability and easy joining which made lead attractive for single houses made it unsuitable for apartment buildings because over a certain diameter the lead pipes collapsed too easily. In Washington, DC, lead service lines were and are most common in older neighborhoods but can still be found throughout the city, in affluent as well as in disadvantaged blocks.

In circumstances where a service line needs to be replaced, a utility does not normally (without special legislation) have the authority to replace the private portion of the service line without the homeowner's permission. Other sources of lead in the distribution system might include lead-containing solder used to join copper pipes, leaded brass components of meters (even some models billed as "lead free"), and faucet valve seats, all of which are inside or attached to the houses and are therefore considered responsibility of the homeowner.

WASA is a relatively young agency, created in 1996 as an independent agency of DC with a regional governing board. It replaced the Water and Sewer Utility Administration, a utilities agency of the Government of the District of Columbia that had experienced a long history of fiscal and management problems.

Owing to its unique status as seat of national government and its status as a semi-autonomous jurisdiction rather than a state, the District of Columbia's water supply is under federal authority. Unusual among metropolitan water utilities in the United States, WASA operates the drinking water distribution system for its customers but does not collect or treat its own water (DC WASA 2008). Water is drawn from the Potomac River, filtered, and disinfected by the Washington Aqueduct, a division of the US Army Corps of Engineers, in an arrangement which dates to the Civil War when the water supply of the capital required military protection. The Washington Aqueduct supplies finished water to WASA, Arlington County and the City of Falls Church. WASA is regulated directly by Region 3 of the US EPA, instead of an autonomous state regulatory agency subjected to EPA oversight, which is the standard practice in the United States (Holder 2004). (EPA is divided for operational purposes into nine regions, which have a high degree of autonomy in their regulatory oversight; Region 3 covers the District of Columbia, Pennsylvania, Maryland, Delaware, and West Virginia from a

regional office in Philadelphia.) This unique arrangement is shared with the state of Wyoming and will continue until the new DC Department of Environment has the capacity to assume oversight and regulatory authority.

WASA's Water Quality Division is responsible for monitoring lead and copper levels. One of the responsibilities of this unit is to coordinate WASA's reporting to the Water Quality Division of Region 3 EPA under the Lead and Copper Rule (LCR) (US Environmental Protection Agency 1991), a regulation promulgated as part of the Federal Safe Drinking Water Act (United States Congress 1974).

Under the LCR, EPA requires that lead in tap water not exceed the designated Lead Action Level (LAL) of 15 parts per billion (ppb) on the specified "first draw" from the tap in more than 10% (i.e., the sample representing the 90th percentile cannot exceed 15 ppb) of tap water samples from homes, after 6 hours of stagnation (i.e. the tap cannot have been used for at least that long). This rather arcane standard for water quality, which was designed as a corrosion control measure, has been the source of much confusion. It is important to recognize that 15 ppb is a "lead action level" (LAL), not a "maximum contaminant level" for lead in drinking water, which is an enforceable allowable upper limit and which is the usual way of regulating water contaminants in the United States and elsewhere. The LAL and the method of determining the LAL are therefore not comparable to the standards of the World Health Organization (10 ppb at any time) or the European Union.

The annual year for sampling and notifying lead levels runs from July 1 to June 30 of the next year (US Environmental Protection Agency 1991). Water is normally tested every six months. WASA qualified for a four month monitoring period under a provision in the LCR for "reduced monitoring" since EPA Region 3 designated optimal corrosion control treatment (OCCT) and WASA consistently met the water quality parameters under the LCR. Under this sampling regime, monitoring occurs during the warmest months of the year between June and September, when lead levels are likely to be highest. The one-litre water samples are to be "first draws" from residents' taps after no less than six hours since last use (this is in practice usually first draw in the morning). The presumption of the LCR is that water collected in this way will reflect

lead levels at the tap derived from either service lines running from WASA's main lines to the house or from the houses' own pipes, meters, and fixtures. (Figure 1) The LCR lead service line sampling requirements do not apply to apartment buildings or schools as these buildings require larger service lines made from a material stronger than lead, such as ductile iron.

An exceedance is not considered to be a violation of the drinking water standard because the LAL is not a maximum contaminant level (MCL). Instead it is a trigger for a set of mandated actions under the LCR, which are described in greater detail below.

Chronology of Events

Water samples had been well below the LAL during the 1999-2000 monitoring period and for a number of years before that. As a result, WASA had qualified for "reduced monitoring" under the provisions of the LCR. Under "reduced monitoring" status, the frequency of monitoring was reduced from every six months to every twelve months and the number of sites required to be monitored was reduced from 100 to 50 collected between June and September. Thus, WASA entered the critical period with no expectation of future exceedance and a reduced monitoring schedule (Holder 2004). The subsequent events have been documented through interviews and discussions with key personnel at WASA, by newspaper accounts, and by reference to several authoritative reviews by both government and private agencies which resulted in detailed reports. (Holder 2004; US Environmental Protection Agency 2004a; DC Office of the Inspector General 2005; US Government Accountability 2004, 2005; DC Appleseed Center 2004; discussions with WASA senior management 2004)

Change in Disinfection Agent

The Washington Aqueduct used chlorine as its disinfection agent until 1 November 2000. It then changed to chloramines, a mixture of chlorine and ammonia, in order to reduce the levels of free chlorine in anticipation of the requirements of the Disinfection Byproduct Rule (US Environmental Protection Agency 1998), which was about to go into effect. The use of chloramines has become standard at many utilities, where it has been effective and generally free of problems. WASA was

consulted on this decision and agreed, as did the responsible oversight authority, the Water Protection Division of Region 3 EPA.

The Washington Aqueduct continued to moderate pH with lime (calcium carbonate) and no other changes in water chemistry were made. The decision to manage pH with lime, rather than the common alternative phosphate, had been made by the Aqueduct in 1994, with the agreement of WASA's predecessor agency.

The US EPA had issued the Disinfection Byproduct Rule as part of a complicated set of regulations to be phased in from 1998 to 2003. These regulations were intended to ensure adequate disinfection of bacterial contamination (as indicated by coliform count, which is used as a surrogate) and to reduce levels of trihalomethane compounds (US Environmental Protection Agency 1998).

2000-2001 Monitoring Period

In the 2000-2001 sampling period (ending 30 June 2001), the Washington Aqueduct received 118 samples (from 62 locations) from WASA to measure for lead levels, but almost half of these were second-draw samples and there were discrepancies because of resident non-compliance, duplication, and reported mistakes in drawing water from the tap. There were 55 acceptable, first-draw, single-site samples, taken during the warm weather months of 2000 and June of 2001, a time when lead levels were likely to be highest because of temperature and when more water is consumed. The 40 samples taken in summer 2000 showed no elevation in lead. Unexpectedly, however, 7 out of 15 of the June 2001 samples exceeded the LAL of 15 ppb.

An administrative decision was made at WASA at a middle-level management position to invalidate some of the samples. Whether or not this was done with prior knowledge and approval of EPA is disputed, (Holder 2004). Consequently, senior management at WASA have stated that they were not alerted and so were unaware of the implications of this deviation from guideline values. The relatively small excursion above historical levels was dismissed initially by the chief operating officer as too small to be significant. In retrospect, the intense focus on regulatory compliance, in which achieving the standard absorbed the attention of management, may have interfered with interpretation of this important

signal that levels were rising and that the system was behaving unpredictably.

2001-2002 Lead Monitoring Data

WASA entered the 2001–2002 monitoring period essentially unaware of the magnitude of the impending problem and committed to a monitoring schedule that may have been inadequate to define the emerging problem.

Continuing on from the trends identified in June 2001, initial results from July and September 2001 showed that among the first 25 samples, 8 homes had levels above 40 ppb, indicating that individual LAL exceedances were being detected more frequently and at higher values in a steady but not dramatic rise. With 8 positive findings out of 50 projected samples, the LAL had already been exceeded for the stipulated 90% of samples for the year under the LCR. Region 3 EPA was therefore notified directly by the Manager of WASA's Division of Water Quality in August 2001 that an annual exceedance was likely. There is a dispute over whether there was timely notification of WASA management. Ultimately, among the 36 samples in July and August 2001, 20 homes exceeded the LAL of 15 ppb (as documented in a communication dated 12 October 2001 between the Washington Aqueduct and WASA). By the end of the monitoring period at the end of June 2002, 26 of 53 samples were above the LAL. The Board of Directors of WASA was informed of the annual exceedance in September 2002 (Holder 2004). At this point, the senior management of WASA had lost a full year of response time. No cause for the exceedance had been found and there was still a strong suspicion that the elevated levels only represented a statistical anomaly. The annual exceedance would trigger a series of requirements under the LCR for which WASA was ill-prepared, but in September 2002 the LCR had yet to be invoked. In September 2002, representatives of WASA and Region 3 EPA met to discuss appropriate customer notification of the elevated lead levels. At this time, WASA's efforts were apparently still oriented toward identifying the problem and ruling out measurement error.

October 2002 and Triggering the LCR

By October 2002, four months into the 2002–2003 monitoring period, it was obvious that the exceedance would continue through

another year and would require concerted action. WASA was now treating the situation as an urgent operational matter but not as a public health crisis and was expecting at that time to receive an exemption from the LCR during the search for a system-wide solution. WASA therefore was caught off guard when Region 3 EPA declared that the provisions of the LCR would be enforced, as of the end of the 2001–2002 monitoring period (Holder 2004).

The LCR is an unusual regulation (US Environmental Protection Agency 1991). Although an exceedance is not technically a violation, it immediately requires five stringent actions from the utility:

- Additional water system monitoring, returning to the more intensive 6-month, 100-sample schedule.
- Water treatment to reduce the source of lead contamination, which usually implies more aggressive treatment of corrosion and pH that leaches lead from lead water pipes.
- Public education, using bill inserts and flyers, using prescribed language that is specified in the regulation.
- Replacement of lead service lines on a specified schedule requiring at least 7% or more to be replaced per year.
- The LCR allows utilities to test houses with lead service lines for lead concentration at the tap and to consider them as having been replaced, for purposes of the LCR, if the concentration is below the lead action level of 50 ppb. These lines then do not have to be physically removed and replaced. (US Environmental Protection Agency 1991)

The US EPA has since completed a review of the LCR, in part because the experience in DC and experiences elsewhere have led to unintended consequences (Cohn 2004a; Leonnig 2004).

WASA duly notified and requested consultation and assistance from the District of Columbia Department of Health and released an announcement of the exceedance to the public (Nakamura 2004a). The first news item appeared on 18 October 2002 in *The City Paper*, a free community publication with a wide local readership. The story indicated that WASA would conduct a public education lead-awareness program,

targeting children and pregnant women. The story attracted no visible public attention.

Public Education 2002–2003

The LCR requires an extensive public education program. It dictates prescribed language to be used in public communications but allows additional material to be added in lay language. The statements mandated in the LCR require a moderately high degree of reading ability in standard English.

As required by the LCR, WASA initially produced public communication materials in late 2002, as listed in Table 1.

“Living Lead Free in DC” was the most comprehensive consumer health publication distributed at that time. WASA sent "Living Lead-Free in DC" to the two major local newspapers, public schools, libraries, and health facilities during Lead Poisoning Awareness Week (20–26 October 2002). The text was based on content provided by the DC Department of Health and used language drawn from, but not precisely following, the LCR. The text was approved by Region 3 EPA. It was criticized much later for being insufficiently explicit about the exceedance because it did not highlight the problem of lead in drinking water, give statistics on lead levels in DC drinking water or convey recommendations for protection of vulnerable consumers. It also had a high English literacy requirement.

In retrospect it became apparent after the public’s reaction in 2004 that the messages disseminated in 2002 were not successful but that may not have been apparent in 2002.

Lead Service Line Replacement 2002 - 2003

Within one year of the initial exceedance, the LCR requires that a plan be submitted to replace all lead services lines in the distribution system on a schedule of at least 7% per year. The replacement of lead service lines is very capital-intensive, costing on average \$5,000 per line. It is also highly disruptive, requiring streets to be torn up and blocked off and trenches to be dug through sidewalks, gardens, and lawns.

WASA had no lead line replacement program in place in 2002 because it had not been needed. As a consequence, the organization was unprepared. A contractor had previously conducted an inventory of lead

service lines known to be in place, estimating 20,000 to 22,000 lines (Nakamura, 2004b). This turned out to be an underestimate and the true number was probably around 35,000. It was already known from the utility's experience that the database had many inaccuracies in recording (informal estimates placed it around 15%) which homes had lead service lines because it had been constructed from work order records which were both incomplete and often in error.

It was physically impossible to replace the required 1,600 lines in the first year. The more known lead service lines that tested with favorable results and were so "deemed" to have been replaced, as described above, the fewer that would have to be replaced, which carried a cost of \$7.5 million per year.

The Board of Directors decided to accelerate the lead service line replacement program on July 1, 2004, in order to complete replacement by 2010. (This was later revised to 2014 and then 2016 when the number of service lines was found to be greater than expected.) This accelerated schedule committed WASA to replacing 10% of lines per year, at a cost of \$100 million over ten years (Nakamura 2004d). WASA prioritized replacement of lead lines serving the homes with the highest lead levels and homes where children lived, in order to protect vulnerable populations first (Holder 2004).

The LCR requires the replacement of the "public" service line, the portion running from the main distribution pipe to the property line of the homeowner. (Figure 1). However, achieving a reliable reduction in lead levels at the tap depends on replacement of both public and private sections. Replacement of the "private" portion, running from the property line into the house, is the responsibility of the homeowner but there is no mandate under the LCR requiring the homeowner to replace the private portion. WASA offered to replace the private part of the line at the same time as the public line at cost (as required by LCR), averaging about \$2,000, but few homeowners complied. Without replacement of the private part of the line, however, replacement of the public portion had a much-reduced effect. WASA therefore arranged for low-interest loans through Wachovia Bank and the DC Council eventually approved a grants program for low-income families (Nakamura 2004c). Even so, fewer than

15% of homeowners took advantage of the arrangements by the end of 2004.

The Public Health Response, 2003–2004

WASA initially turned to the DC DOH for assistance in preparing the document “Living Lead-Free in DC” in September 2002, at a time when the DC DOH was able to provide such technical support. Shortly thereafter, DC DOH entered a period of instability during which it lacked the capacity to provide stable, consistent support. Subsequently, in mid-to late 2004, the Department responded with the enhanced screening program and joined WASA, the Washington Aqueduct, and Region 3 EPA in a series of community meetings to show consensus on the health message WASA contracted with our academic unit to provide public health and risk management expertise directly, as consultants to the utility, which led to the present work.

Following the LCR and guidance from Region 3 EPA, WASA instituted a series of recommendations and advisories for families living in homes with lead lines or those that returned elevated levels of lead in tap water: Specifically, WASA:

- Recommended that water lines be flushed for 10 minutes before consuming drinking water. (Initially the recommendation was for 90 seconds, which is sufficient to deliver lead-free water from the main. Water filters were distributed to all homes where the LAL was exceeded and later to all homes with suspected lead service lines. Replacement filter cartridges were sent to the same homes at six-month intervals.
- Homeowners continued to be offered the services of WASA’s contractors to replace private lead service lines at cost at the same time that public lines were replaced.
- WASA continued its public outreach, offering testing to any property owner and resident who wished it.

Visibility and Risk Perception, 2003–2004

Although the first newspaper report on the lead elevation did not draw much public interest, a front page article of *The Washington Post* (January 31, 2004), received national attention and elicited considerable local concern, as indicated by the frequency of telephone calls and

attendance at community meetings. The media coverage that followed declared this issue as a “public health crisis” (Nakamura 2004e). Numerous articles in the *Washington Post* and other media criticized WASA for changing its recommendations over time in the face of new evidence. The *Post* also identified tap water lead levels by individual home addresses obtained from a web-accessible database. (WASA policy is not to release such data.) (Nakamura 2004f)

Adding the perception of a public health risk during the period of peak interest was a series of stories on water fountain lead testing in schools (Paley 2004). The EPA guidance on testing schools is different from that applied to homes under the LCR. Testing is voluntary on the part of school districts and standards are based on a maximum allowable level, not the corrosion-derived method for examining behavior of the distribution system that is used in the LCR. Several samples taken in school drinking fountains and faucets exceeded the guidance of 20 ppb and a few showed markedly excessive levels (one exceeded 4000 ppb in taps that were, however, seldom used or flushed. Although presented in the media as part of the same story, the issue of lead in drinking water in schools is distinct and relates specifically to the maintenance of school property. At the time, there was also a similar but unrelated issue playing out in the media with WASA’s sister utility in suburban Maryland. To the casual reader, therefore, it appeared that drinking water throughout metropolitan Washington was unsafe and even dangerous.

Risk Management in 2004

While these other events were occurring, WASA attempted to determine the actual cause of the elevation and to identify ways to mitigate the problem. It was assisted by a Technical Expert Working Group, an ad hoc group of advisors convened jointly by WASA and Region 3 EPA (US Environmental Protection Agency 2004b). WASA also began doing pipe-loop corrosion experiments (Cohn 2005). These experiments involve circulating water through removed sections of water pipe to determine the effect of chloramines on water lines, in the context of its own system and water chemistry.

In 2004, an opportunity arose for a natural experiment on the system. An annual system-wide pipe flushing was scheduled for April and May to remove sediment. During this flushing, the Aqueduct returned to

chlorine on a temporary basis. Lead levels fell throughout the system, strongly suggesting that the problem arose with the change in disinfection agent (US Environmental Protection Agency 2004c; American Water Works Association 2005). The working theory was that rather than increasing corrosion directly, the switch to chloramine had reduced the tendency of metals and residue on the surface of the pipe (scale) to form reversible complexes, which had the effect of enhancing the leaching of lead. A permanent return to chlorine was not possible, however, because of the Disinfection Byproduct Rule.

The Washington Aqueduct and WASA, with approval from Region 3 EPA, then determined that addition of phosphate, in the form of orthophosphate (phosphoric acid), would act to stabilize these surface complexes over time, although the effect would take many months. This was tried on a pilot basis in one segment of the distribution system and caused no untoward effects. On August 23, 2004, phosphate was introduced system-wide. Subsequently, the lead level in tap water slowly fell and has been compliant with the LCR since 2005.

Analysis

The response to the lead issue and the requirements of the LCR severely strained the operational capacity of the organization. WASA faced a crisis of credibility during a period when the organization was still relatively new and while the position of public affairs director was vacant. By the end of 2004, WASA had expanded its public relations and legal staffs (Nakamura 2004g), hired a team of academic consultants on risk management from The George Washington University (Nakamura 2004h), staffed fully its research and development laboratory, assembled its own team of experts and consultants, and pulled together a network of contractors capable of replacing 1,615 service lines per year.

Early Events

None of the parties involved initially seems to have considered lead levels in DC drinking water to be a warning of a deeper problem because it had never been a problem since the creation of WASA. The elevations in July 2001 were considered an anomaly that did not reflect a true change in water chemistry. WASA's orientation at the time was toward compliance, not risk management; if a final result was in

compliance with the LCR, there was no mechanism in place to identify trends or to anticipate the risk of future problems. Since management and accountability systems were not set up to assess anomalies in the performance of the system in 2001 and because the organization had focused narrowly on compliance, WASA was caught off-guard and a year later had to scramble to meet the requirements of the LCR.

The risk communication challenge was as severe as any faced by a water utility in modern times. Key lessons learned from this experience include that risk communication, crisis communication, and corporate communication are separate and distinct. They have different dynamics and methods. Risk communication is about what a potential hazard means for individual people and families. Crisis communication guides people through a period of perceived danger or a dislocation in their lives. Corporate communication informs people of the purpose, responsibility, and assistance provided to them by the organization. The one factor all three communication types have in common is that both are most effective when they focus on what people want to know and not on what the organization thinks they should know.

Education on the context of an issue, in this instance the water distribution system, is difficult in the middle of a crisis when one message, in this case the health risk, dominates other messages. We recommend that water utilities use the period between crises to lay the foundation for understanding the issues. In this case, WASA's risk communication message would have been easier for the public to accept had there been a better understanding of the water distribution system as a whole. On the other hand, it is hard to imagine the public taking an interest unless there is a problem.

It is essential to build partnerships in advance of a crisis. Had WASA and DC DOH had an effective working relationship before the incident, the initial response might have been more appropriately focused on water. Such coordination is admittedly difficult where there is discontinuity in leadership, as occurred with the DC DOH. By coordinating their messages and press releases, the Washington Aqueduct, WASA, Region 3 EPA and the DC DOH were ultimately able to achieve a harmonized message at community meetings and avoided the appearance of conflict and contradiction.

Acknowledgement:

This study was supported by a contract from 2004 through 2008 between the DC Water and Sewer Authority and the George Washington University, which was retained to provide assistance to WASA in risk management. We thank WASA for technical information and figures and for providing documentation to confirm the accuracy of the chronology. WASA has been renamed “DC Water”.

This paper was originally accepted by the Journal of Water and Health in 2008. The paper was withdrawn by the authors before publication to avoid entanglement in a highly visible legal action (Parkhurst v. DC Water and Sewer Authority). The authors felt that because the same evidence was expected to be presented in court, publication before trial would inevitably be construed as an attempt to influence the decision. Four coauthors withdrew from authorship in 2008 in response to a climate of intimidation that prevailed at the time. The legal action was dismissed in 2016.

Aside from this acknowledgement, which was added in 2018, this paper was written in stages from 2004 through 2008 and is unchanged from the original submission. It therefore represents a preserved contemporary record.

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Figure 1. Schematic drawing of the water distribution system from the water main to inside the house.

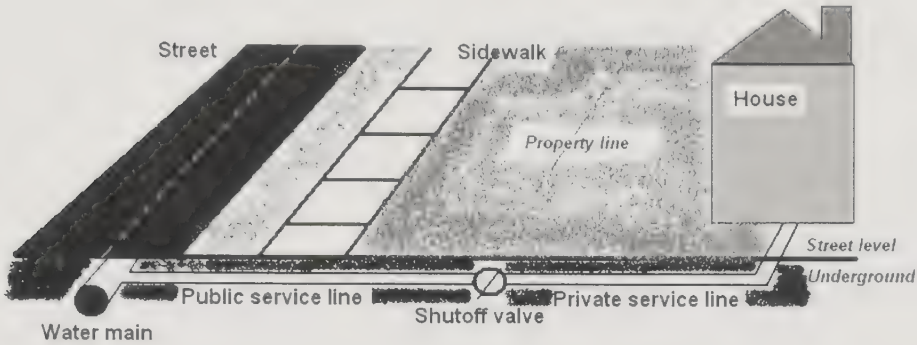


Table 1. Public Communications by WASA in 2002 and 2003.

- Mailings, initially special mailings and later inserts with bills mailed to customers.
- A section on the exceedance in the annual Consumer Confidence Report, a federally required report on water quality and service designed for customers.
- Public service announcements on local media, primarily radio. When these were perceived to be ineffective, largely because they were broadcast infrequently and during late hours, WASA purchased advertisement slots to run on local broadcast channels during peak hours.
- A special Water Quality Report, “Your Drinking Water is Safe,” reinforced by media appearances by the WASA General Manager.
- “Living Lead-Free in DC”, a glossy 12-page booklet, was released in October 2002 for Lead Awareness Week in collaboration with the DC Department of Health.
- A telephone hotline was established in January 2003 to collect citizen complaints and to provide information.
- Public meetings were convened beginning in May 2003. Initial turnout was low.
- A message was placed on the water bill itself in August 2003, as required by the LCR.

Fifteen Years Later: Notes on Lead in Drinking Water, Washington DC, 2004

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Abstract

In 2004 Washington DC (“the District”) experienced an environmental health crisis involving elevated lead levels in drinking water. Fifteen years on it is time for a reassessment. The impact on Washington was nothing like that of the appalling situation in 2014 in Flint, Michigan, other than that lead was involved in both. The situation in Washington arose as an unintended and unexpected consequence of measures to reduce the levels of halomethane compounds in drinking water to reduce the potential for cancer risk. The problem ended with a simple and very conventional solution, the judicious application of a nontoxic chemical treatment already commonly used to correct water chemistry (zinc orthophosphate). DC public school students who were at a susceptible age in 2004 have achieved major gains, not losses, on national standardized education tests.

Introduction

IN 2004 WASHINGTON DC experienced an environmental health crisis involving elevated lead levels in drinking water, leading to fears of lead poisoning and learning disabilities among District children. There were two levels of potential risk: an increased frequency of lead poisoning in the short term, which was effectively ruled out, and a subtle and difficult to characterize prevalence of neurotoxicity in the long-term that probably could not be documented. In the end the risk was mitigated first by a public notification campaign (as required under the relevant regulation) and provision of free water filters to residents, and second by passivation of the water system with a safe and widely used water additive.

At a point where the worst of the risks did seem to have been ruled out, a massive class-action lawsuit (Parkhurst v. DC Water and Sewer Authority) was filed in 2009 for alleged damages, demanding \$200 million from the water utility, which would have added roughly \$1300 to the water bill for every household. Worse, thousands of infants and young children who were growing up in the District could easily have been labeled as at

risk, mentally and in learning ability, by those who did not understand the science but read the headlines, including parents who had diminished expectations for their children, school admissions officers outside the area who may have doubted their potential, and future employers who would have new grounds for discrimination.

Fifteen years on, it is time for a reassessment to determine the actual lessons learned. Since 2004 DC public school students who were at a susceptible age have achieved major gains, not losses, on national standardized education tests. (Tuque, 2011, Brown 2013) The number of cases of children with diagnosed lead poisoning (by the definition current at the time) did not spike. The problem ended with a simple solution, the judicious application of a nontoxic chemical treatment commonly used to correct water chemistry (zinc orthophosphate). (While no chemical is entirely free of toxicity, orthophosphate comes close.) The class certification and eventually the whole legal action were dismissed. In the end the impact on Washington was nothing like that of the horrendous lead issue that erupted in 2014 in Flint, Michigan, which it in no way resembles other than that lead was involved in both. The situation in Washington arose as an unintended and unexpected consequence of measures to reduce the levels of halomethane compounds in drinking water in keeping with existing procedures, regulations, and water treatment processes. Flint, on the other hand, was a predictable and avoidable crisis created by malfeasance, mismanagement, and political interference with an essential public health function. It was also one of several closely interrelated public health problems related to water at the time. (Clark, 2018)

Lead exposure is *always* a legitimate public health concern regardless of source, because the neurotoxicity of lead shows no threshold for children. The incident in the District was the first national experience with a technological innovation in water disinfection that backfired. It was a wake-up call to the legacy risks associated with the lead-dependent water distribution system in older cities. It was important locally as the first trial under fire of the newly reformed DC Department of Health (DOH), which in 2003 had been in a near meltdown and in 2004 was under new, untested leadership. In the end the incident had the positive effect of drawing attention to the most important source of exposure, which is peeling leaded interior paint in houses, and resulted indirectly in a much improved lead

law, the DC Lead Hazard Prevention and Elimination Act of 2008 (amended in 2010).

The present paper is intended to lay out the issues *as they were seen at the time*, from the point of view of a university-based consultant in public health to the water utility, then called the DC Water and Sewer Authority (WASA), who also worked closely with the DC Department of Health (DOH) at the time.

Background

Water from the Potomac River watershed is essentially free of lead. Lead in drinking water does not come from the source or from surface pollution but from soluble lead migrating into the water flow from the components of the water distribution system. These include the interior surface of lead “service lines”, lead-containing brass fittings, older water meters, solder joints, and faucets. Service lines are lead pipes that carry water the last few meters from the water main (running under the street) to the house. Service lines carrying water to houses, but not to larger buildings, were almost always made of lead until the 1930’s, when they began to be replaced in new construction by copper. The transition was largely complete by the 1950’s. (Rabin, 2008) The result has been a legacy of buried lead pipes in older neighborhoods and cities. These “lead service lines” are expensive to replace (usually with copper for single-family houses) and when this is done the old lead lines are usually left in the ground, unconnected.

For many years, until the turn of the last century, drinking water was among the most important sources of lead intake in the United States, other than occupational exposure. (Troesken, 2006) Improvements in the drinking water distribution system led to a gradual reduction of waterborne lead exposure, despite the presence of lead service lines. At the same time exposure to other sources from lead was considerably reduced or, in the case of lead in gasoline eliminated altogether beginning in the 1970’s. The mean blood lead levels of children declined dramatically, in parallel with airborne lead levels. (Pirkle, 1994) This decline was also seen in Washington and was sustained until 2001, when there was a small rise (to be discussed below) followed a year later by a return to the declining trend.

In 2000 Washington DC, for reasons of federal prerogatives and jurisdiction, had something of a test case for changes in drinking water chemistry. The US Environmental Protection Agency (EPA) had mandated a national conversion in disinfection agents, critical for the prevention of waterborne disease, from chlorine to chloramines, in order to reduce the formation of potentially carcinogenic organic compounds in water (trihalomethanes). This was initiated in Washington in January 2000. Unexpectedly, because chloramines had not had this effect in other settings, in Washington lead levels rose inexorably in tap water but for a long time still remained below the regulatory standard (to be explained below). The change in water chemistry that resulted had eluted soluble lead by converting insoluble tetravalent Pb(IV) to soluble Pb(II), a reaction discovered by the EPA's Michael Shock, but not understood in 2004. (Renner, 2006)

Exactly when this slow increase in water lead levels was noticed for what it was and whether it was properly reported to senior management has been a matter of contention and litigation, complicated by a confusing legal action over removal of the compliance officer. However, in retrospect it is abundantly clear that had the rise in water lead levels over 2001 and 2002 been appreciated and assumed to be real, and not thought to be a statistical fluke of sampling, the response would have been more robust and timely.

By mid-2002, the provisions of the Lead and Copper Rule (LCR) were triggered. [Note: The EPA announced on 10 October 2019 that the LCR will be revised.] The [current] LCR prescribes monitoring for lead in water at the tap, mandates measures to be taken in the event of an elevation over the allowable level of lead at the 90th percentile of samples, and requires scheduled replacement of lead service lines, which is a very expensive proposition. The issue had generated its first news story (in the *City Paper*) (Levin, 2002) and a public information campaign was in progress. The DOH had been called in but was not providing WASA needed support and advice because of its internal issues.

This incident was widely presumed at the time to be a classic issue of environmental justice, but it was not. At that time, there was not a strong association between housing quality and price and the presence or absence of a lead service line, although there probably is now. They could be found in every ward, in houses in all price ranges, including the most expensive.

and were not concentrated in poor or disadvantaged neighborhoods. Washington has gone through an extensive period of housing rehabbing, renovation, and restoration, which means that homeowners with resources are much more likely to have largely replaced lead services lines and remediated lead paint, while disadvantaged owners may have not and so housing quality is becoming a better marker for the presence of a lead service line than it was in 2004.

Fifteen years later Washington DC still has many lead service lines that have not been replaced because of the cost (\$5000 per house). Replacement is legally the responsibility of the homeowner because the District does not own the service line. (This is not true for other cities, such as New York.) In practice, part of the line does run through city property but partial line replacement is only partially effective and may create a new opportunity for spiking lead levels at the tap. From about 2005 to 2008, there was some interest in a comprehensive lead service line replacement program but this diminished because appropriate water treatment had brought lead levels under control by then. (We proposed at a hearing in 2008 that there be mandatory total replacement funded as a deduction from money transfers for real estate sales at the time of closing, but that proposal did not get any traction, presumably because of the added expense in a less robust real estate market.) Ultimately, enthusiasm for a permanent solution gave way to acknowledgement of the exorbitant cost and reliance on current water treatment practices to forestall a recurrence.

Exposure Assessment

Since well before the creation of the EPA, the primary strategy for control of lead in drinking water has been to ensure that water flowing through the service line is rendered chemically unreactive (passivated) with the interior surface of the lead pipe. This is normally accomplished by controlling the pH, by adding orthophosphate (a nontoxic chemical that passivates the line), or not overtreating the water so that it becomes too “soft” (reduced in calcium and magnesium ion content, which promotes leaching of lead).

Exposure assessment for lead intake can be difficult, especially quantifying intake from water. Methods that quantify daily intake require accurate measurement of both the concentration of lead in the water

consumed and water consumption habits. Children, in general, consume more tap water than adults. Most people in modern society tend to consume more processed water than tap water, in the form of commercial beverages, and consume much of their water intake outside the home, for example at work, in restaurants, and at school. The major exception is infants whose sole or main source of nutrition is formula made from tap water. Formula might be made once or twice a day and would therefore reflect the lead content at the time it was made, which is disproportionately likely to be in the morning, after overnight stagnation.

Water distribution systems are highly variable, both within any one system and among different systems. The LCR protocol was designed as a measurement to track system-specific corrosion performance, not as a health standard, although the ultimate purpose in driving a reduction in lead content in drinking water is of course to protect health. The key to that is control of the “corrosivity” of water throughout the system. Corrosion control monitoring in the United States, uniquely, monitors lead and copper concentrations in “stagnated” water (water that has been allowed to rest in the distribution system for a time) with a statistical target for the 90th percentile of samples rather than a maximum allowable or permissible concentration. The protocol used for measuring lead in tap water under the Lead and Copper Rule (LCR) is a compliance measure, designed to ensure that the distribution system as a whole is not experiencing aberrant swings in lead concentration. It has been appropriated for use as a surrogate group measurement for lead exposure but it was not designed for that purpose. This concept is key to understanding what follows.

The selection of houses is made from a predetermined panel of participating households with geographic dispersal within the water system. In Washington participation on the part of homeowners in testing has been a problem for many years. Samples are taken at the tap within thirty seconds or one minute from “stagnated” water that has not run for at least six hours. The LCR has a provision for a reduction in sampling when a water utility has been compliant for a long period and no problem is anticipated. In 2000 and 2001, WASA was on an EPA-approved reduced-frequency sampling program because a lead exceedance had not occurred for many years. (With the benefit of hindsight, it is clear that the sampling schedule should have

been returned to normal frequency during the transition period, in preparation for unanticipated consequences.)

The water samples taken in a particular period are tested for lead and ranked. Most will be very low and some even close to zero. However, the measurement of the sample at the 90th percentile (90thile) is compared to a standard called the “lead action level” (LAL), which under the LCR is 15 ppb. The LAL does not apply to levels > 15 ppb in any individual sample, only to the 90thile in the set of samples. Statistically, this protocol operates as if one were tracking the overall academic performance of a school by following the test scores of D students (above failing but doing worse than other students when graded on a curve), assuming that majority of students were getting passing grades and did not require close attention. Such a system would be good at identifying schools that were producing more students who were at or close to failing but would say very little about the performance of the average or well-performing members of the class. Similarly, the LCR protocol is designed to flag water distribution systems that are at or coming close to elevated lead levels in water in some of the taps in their distribution system but it does not provide a measurement or even a reliable indication of how much lead is in water actually consumed from the tap. The methodology for determining how much tap water is actually consumed and calculating the lead content is highly dependent on recall or direct subject monitoring at the point of consumption. There is no reliable methodology for estimating this from population-level data.

The LAL was created to benchmark the behavior of the water distribution system, not a cutoff for an individual sample of water, a maximum allowable level for the water supply, or a health risk-based standard. In most countries, and in the US for other contaminants, the usual approach to setting standards to regulate water contaminants is to compare water concentrations against a “maximum contaminant level” (MCL), which is an enforceable allowable upper limit that applies to all drinking water, all the time. (World Health Organization, 2006) Lead is the exception precisely because lead comes from the distribution system, not from the source or external contamination, and so most samples test close to zero and only the higher measurements matter in the distribution. For that reason, the shape of the curve is hyper-exponential or J-shaped, not normally or linearly distributed, and the 90thile is a benchmark for the position of the curve, not

a cutoff for allowable concentration for any one sample. An MCL for lead could, in theory, allow lead at a concentration just below that level for all water consumed, which would lead to much greater intake of lead from water than the LAL, which defines the distribution of a curve in which most values are close to zero and sends a warning when the curve has shifted that the system is has changed its performance characteristics.

A secondary issue that emerged during the controversy is the chemical form of lead and the implications for bioavailability. Most bioavailable lead in drinking water is solubilized lead present as a dissociated lead salt. Measurements of “total lead” in water may include poorly soluble particulate lead that is solubilized by the analytical procedure but is not in a form readily absorbed by the body. The “approved methodology” for preparing water for lead determination is EPA Method 6020, which involves adding nitric acid to dissolve lead in the sample at pH 2 before it is tested. Nitric acid was chosen specifically because it is capable of dissolving lead completely. However, the acid produced in the stomach is hydrochloric acid, not nitric acid. Almost uniquely, hydrochloric acid does not readily dissolve lead because it forms chloride complexes. Gastric peristalsis then carries lead particles into the gut, where the pH is high and absorption is low.

EPA Method 6020 is designed to increase the sensitivity of lead detection and to ensure that small particles of lead are accounted for as well as dissolved lead, not to reproduce physiological conditions after ingestion of a lead particle. When nitric acid is used in lead determination, it dissolves particulate lead and lead-containing flakes of scale prior to water analysis. This does not reflect effective exposure and absorption from stomach contents.

By comparison most lead used in leaded paints were in the form of lead salts, principally lead carbonate (PbCO_3). The solubility and bioavailability of lead carbonate, together with its sweet taste, is precisely why leaded paint chips are so toxic and dangerous to children.

Correcting the Record on the 2007 Paper

In 2007, we published a study of 6,834 subjects who had received blood lead level (BLL) determinations in a six-month period in 2004 during which the DOH ran a supplemental lead screening program for District

residents. (Guidotti, 2007) This expanded lead screening program was a public health intervention, in which the objective was to identify children with elevated blood lead levels. At the time, as now, the threshold for considering the level to be elevated was a blood lead in children above the CDC's "level of concern" by the definition at the time, which is universally considered too high today (10 µg/dl). DOH kept the data confidential and did the analysis in house but our team evaluated the findings at the request of the DOH. 65 children were found to have "elevated" blood lead levels, about as expected.

There were four indicators of public health impact derived from the data presented in the study. The first was the median blood lead level for children in the screening program, which was slightly less than the median for US children in urban areas. The second was the distribution of blood lead levels, which if there were an affected subgroup might be expected to show a bimodal distribution or at least a fat tail of the curve; no such second mode was present. The third would have been the identification of cases in which no obvious source of lead exposure was found; only two such cases were identified and in neither was lead in drinking water found by the DOH to have been a plausible source. The fourth was the lack of a correlation between elevated lead in drinking water in homes and elevated blood lead levels in children from those homes, when paired data were examined in two convenience samples. At the time, we were also aware that there had been no spike in lead poisoning cases reported for evaluation and treatment in the District, but did not publish this as a fifth indicator because we did not have the actual number. The number of children with elevated blood lead levels at that time usually numbered between 150 and 200 per year in Washington DC at the time and 2004 was not exceptional. We did not do a longitudinal analysis of lead levels because we had been warned that the DOH data from 2003 were incomplete.

An important subgroup finding in our paper, discussed at length, was the demonstration that children living in homes with lead service lines showed higher blood lead levels than children living in homes without such lines. This finding had been seized upon as *prima facie* evidence for a waterborne lead risk. However, houses that had lead service lines in 2004 were also much more likely to retain interior leaded paint because they had not undergone rehabbing, whereas houses without lead service lines were

either of more recent construction or if older were more likely to have been rehabbed. This is because of the provision of the DC Plumbing Code mentioned earlier. Therefore children living in houses with lead service lines were almost certainly also at greater risk for background lead exposure from dust and the opportunity for catastrophic exposure to paint chips and consequent lead poisoning, simply because the presence of the lead service line was a marker for a house that was older but had not been rehabbed.

In 2004 we approached the EPA Office of Water and asked for clarification on predictions of the pharmacologically-based toxicokinetic (PBTK) model in the version then in use by the agency, the so-called IEUBK. This model is known routinely to overestimate the contribution of water intake to blood lead because of its default assumptions. Despite its limitations we wanted to quantify the sensitivity of blood lead to intake from water in young children. In response, the National Center for Environmental Assessment did a set of simulations to determine the concentration of lead in water that would be required to change blood lead levels under three conditions, in the presence of standard default conditions of intake from food and other sources: 1) change by a detectable amount, 2) contribution sufficient to reach a significant level potentially associated with subclinical toxicity (5.0 $\mu\text{g}/\text{dl}$) from water alone, and 3) contribution sufficient to reach the CDC “level of concern” (10.0 $\mu\text{g}/\text{dl}$) from water alone. (EPA, 2004) The Office of Water graciously did so and informed us that the threshold level for a detectable change (defined as 0.1 $\mu\text{g}/\text{dl}$) was estimated to be approximately 7.1 ppb (= $\mu\text{g}/\text{l}$) for 1 to 2 year olds and 6.7 ppb for 2 to 3 year olds. The level associated with a blood lead level of 5 and of 10 $\mu\text{g}/\text{dl}$ (the “level of concern” at the time) was approximately 21 and 24 $\mu\text{g}/\text{l}$, respectively. The level required to reach a blood lead level of 10 $\mu\text{g}/\text{dl}$ was approximately 93 and 96, respectively, for regular, sustained intake throughout the day. These are figures for continuous intake, however, not peaks. (EPA, 2004; memorandum from Robert W. Elias to Edward V. Ohanian, 30 August 2004) Since the background level in water is zero most of the time, it seems clear that by the IEUBK, drinking water is unlikely to be the major contributor to blood lead levels.

There were other studies. Their authors will have to speak for themselves if they care to but none has received, and withstood, the same scrutiny as the 2007 paper. Shared limitations in other studies were over-

reliance on modeled or incomplete rather than actual outcome data, limitations in exposure assessment, neglect of obvious confounding factors (and a striking incuriosity to resolve spatial anomalies despite the availability of data to do it), and lack of appreciation for exposure-response relationships in drawing conclusions. Because of the prominence of the issue in the Nation's Capital and the significance of the event as a portent for future unwelcome surprises, we advocated at the time for a thorough review of all available studies by an authoritative neutral party (we preferred the National Academies). That did not happen and as a result numerous incomplete and uninformative summaries of greater or lesser detachment (distinct from objectivity) circulated, most of which betrayed a lack of appreciation for the technical aspects of the problem and so tended by default to look for evidence of malfeasance or environmental injustice.

Conclusion

Controversy over the relationship between lead in drinking water and risk of elevation in blood lead is missing the point. Whether formally defined as "elevated blood lead level" by the CDC level of concern or the population distribution, there is no compelling evidence at present that drinking water at levels commonly encountered in the community and in compliance with the LCR contribute more than marginally compared to historical risk in children. Elevations not far above the LCR are unlikely to be drivers of blood lead levels except perhaps in infants, who may be at risk under special circumstances if formula is prepared from first-draw water and boiled down. That does not negate the general principle that sound environmental and public health management oblige us to reduce exposure to lead from all sources to as low as feasible, as we made clear in the 2006 article. It is also clear that as historically more significant sources of lead exposure decline, the contribution from sources of lesser magnitude becomes more visible and proportionately more important. Regardless, we should be clear that lead paint and lead-containing dust continue to be the major driver for lead exposure in young children and the debate over water should not distract us from addressing this priority.

What happened in Washington DC in 2004 and in the years just prior is a case study in the public health management of an unanticipated environmental hazard. It is also a cautionary tale of how environmental epidemiology can be mismanaged. Studies in the real world of public health

are not clean, controlled trials. It is not appropriate to treat a population-level case study on the same terms as a toxicokinetic study. It is also not appropriate to dismiss basic issues of confounding or temporality as irrelevant because they do not fit a preconceived narrative. The rancor on display was also totally uncalled for.

Most authors commenting on the events miss the essence of the problem in Washington, DC, which has been that Washington has historically experienced a high frequency of individual cases of elevated blood lead level but not a high mean blood lead level, and continued to show this pattern throughout the period of concern.

The frequency of elevated blood lead levels are driven by the probability of encountering a critical exposure source but because this involves a relatively small number of children, rare elevated levels do not affect the mean for a large population. The exposure source of significance for individual cases of elevated blood lead is overwhelmingly lead paint in older housing units. Once a child encounters a single leaded paint chip, the contingent probability of an elevation in blood lead level is very high and the result may be catastrophic. Since relatively few children encounter lead paint chips compared to the entire population of children and fewer still encounter other concentrated sources, the exposure sources for the population as a whole are predominantly food and dust, with water playing a secondary role.

All sources of lead should be controlled to the extent possible because they all contribute to body burden and cumulative effect. That, and the historical fact that in the past water was associated with high exposure in some situations (Troesken, 2006), makes it necessary to remain vigilant and to continue to regulate lead in drinking water. Indeed, this is precisely the reason we studied this topic in the first place.

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Bio

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Acknowledgement:

The initial study was supported by a contract from 2004 through 2008 between the DC Water and Sewer Authority (WASA) and the George Washington University, which was retained to provide assistance to WASA in risk management. We thank WASA for technical information and figures and for providing documentation to confirm the accuracy of the chronology. WASA has been renamed “DC Water”.

AstroBite – An Impossible Black Hole

The latest science news mentions the discovery of an impossible black hole. Black holes are strange celestial objects that apparently litter out Universe. They result from Einstien's General Theory of Relativity, but were mentioned in theory much earlier (see Howard, *JWAS*, **97**, 1 (2011)). Astronomers think that stellar sized black holes result from the end process of a massive star – one that is originally many times the mass of our Sun. The star implodes after scattering stellar remnants back into space, leaving behind a singularity. Mathematically this becomes a one divided by zero spot. One divided by zero is undefined. It is not zero; it is not infinte; it is undefined. The laws of physics do not apply and cannot be used. This undefined spot is called a singularity in spacetime. That singularity is a black hole. We cannot see it; we cannot touch it; we cannot escape it if we get too close. We can describe its environment, at least up to a point. Black holes were considered a mathematical curiosity until the 1950s. By the 1960s black holes were shown to result from the General Theory of Relativity.

In addition to stellar sized black holes (ones that are the result of star's implosion process) there are supermassive black holes that have masses many millions of solar masses. These supermassive black holes tend to lurk in the centers of galaxies. There is one in the center of our own Milky Way.

Black holes do not zoom around the Universe gobbling up stars. They tend to sit quietly where they were formed. However they compress a lot of mass into an extremely small point. A lot of mass in a teeny space means that the gradient of its gravitational field is quite steep. If a star gets close enough (and that is pretty close), it will inexorably be drawn into the black hole. The same amount of mass in a large space (like our Sun) does not have a steep gravitational gradient. It does, however, have the same gravity as a one solar mass black hole. If the Sun were to become a black hole, the Earth would continue to orbit as it had been orbiting. It is not close enough to get drawn in. In the case of a one solar mass black hole, close enough means within three kilometers.

So what is an impossible black hole? Well a group of Chinese astronomers have discovered a black hole 70 times the mass of the Sun. This is about twice what current stellar evolution models can predict. In other words a

massive star can implode to produce a black hole of about 30 solar masses. But current models do not predict any larger stellar black holes.

In 1783 English philosopher John Michell (the first person to propose the existence of black holes) suggested that black holes may be detectable if they were orbited by something that does emit light - such as a companion star - which would be tugged around the resulting binary system's mutual center of gravity.

This is now known as the radial velocity method, and it is one of the main ways astronomers search for and confirm the existence of hard-to-see exoplanets as they exert a small gravitational influence on their stars. If it works for the almost invisible exoplanets, it might work for an invisible black hole. So Jifeng Liu of the National Astronomical Observatory of China and his colleagues used the Large Sky Area Multi-Object Fiber Spectroscopic Telescope in China to search for these wobbling stars, and found one – a main-sequence blue giant star. The result is published in *Nature*.

Follow-up observations using the Gran Telescopio Canarias in Spain and the Keck Observatory in the US revealed the nature of what they had found. The blue giant star, around 35 million years old and about eight times the mass of the Sun, is orbiting the black hole every 79 days on what the researchers called a “surprisingly circular” orbit. “Black holes of such mass should not even exist in our galaxy, according to most of the current models of stellar evolution”, said astronomer Jifeng Liu.

So here is our impossible black hole. It will drive a host of follow up observations and theoretical work. It is too big to be a typical stellar mass black hole and far too small to be a supermassive black hole. It is a classic case of neither big enough nor small enough to exist. Maybe we will find that a new class of middle sized black holes exists. We shall wait and see.

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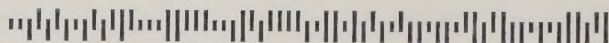
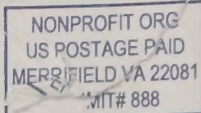
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